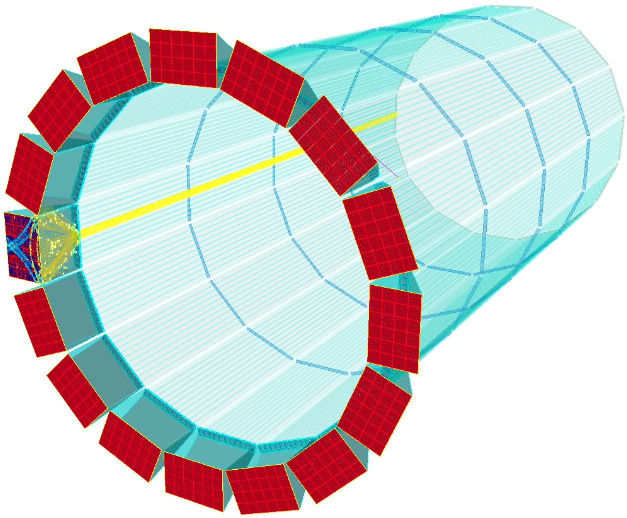
The High-Performance DIRC for the EIC

Directed R&D Proposal to mitigate key risks



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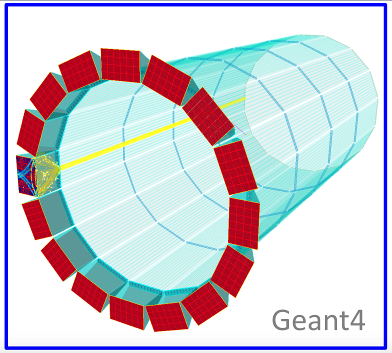
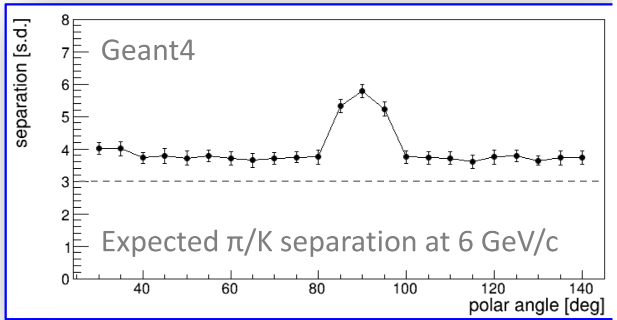
High-Performance DIRC Goal:

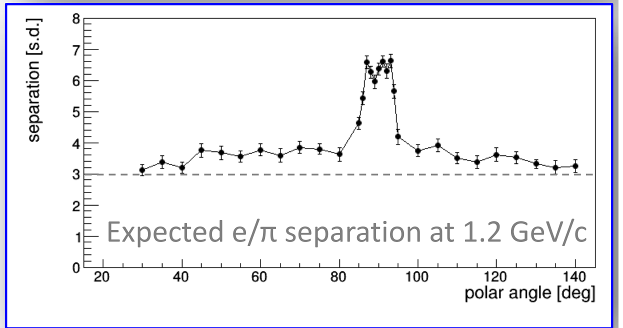
- To develop a very compact barrel EIC PID detector with momentum coverage reaching 6 GeV/c for π/K, pushing the performance well beyond the state-of-the-art for DIRC counters.



Concept:

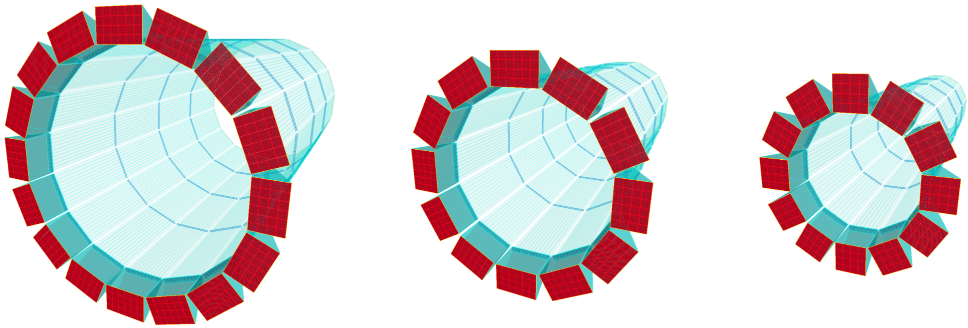
- Fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction
- Initial generic design (based on BaBar DIRC, R&D for SuperB FDIRC, PANDA Barrel DIRC): narrow fused silica bars, 1m barrel radius, 4.5m barrel length
  (barrel length and radius to be optimized for detector integration - no impact on DIRC PID)
- Innovative 3-layer spherical lenses, compact fused silica expansion volumes
- Fast photon detection using small-pixel MCP-PMTs *(eRD14)* and high-density readout electronics *(eRD14)*
- Detailed Geant4 simulation:
  40-120 detected photons per particle, ≥ 3 s.d. π/K separation at 6 GeV/c





hpDIRC R&D Priorities

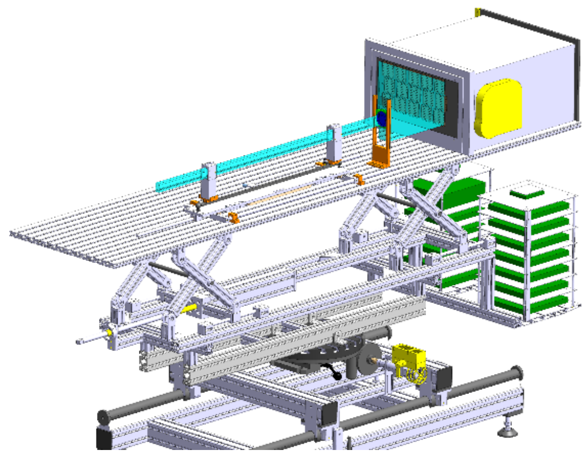
hpDIRC is the baseline hadronic PID system for the EIC detector barrel in all three proposals



- ATHENA and ECCE: hpDIRC with reused BaBar DIRC bars
- CORE: low-mass hpDIRC with new, thinner radiator bars
- Demanding project schedule: CD-2 (1/2023), CD-3 (3/2024)

R&D Priorities: Minimize risks, realize opportunities

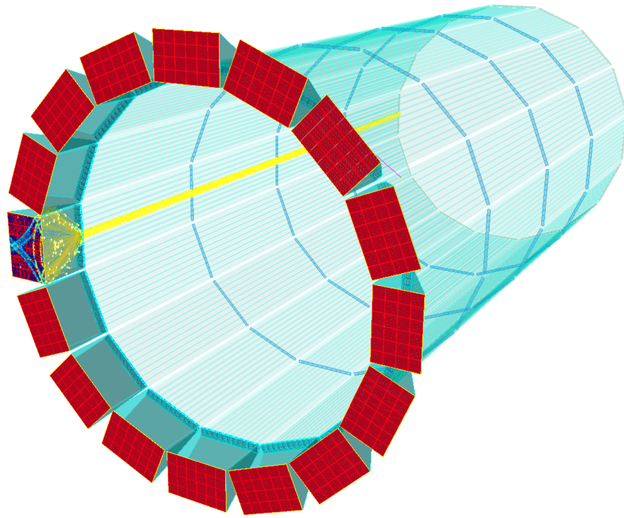
- Technical risk: hpDIRC PID baseline design validation
- Technical risk/opportunity: narrow bars with wide plate hybrid design
- Opportunity: cost/performance optimization
- Technical risk: small pixel photon sensor and fast readout electronics performance
- Technical risk/opportunity: reuse of BaBar DIRC bars

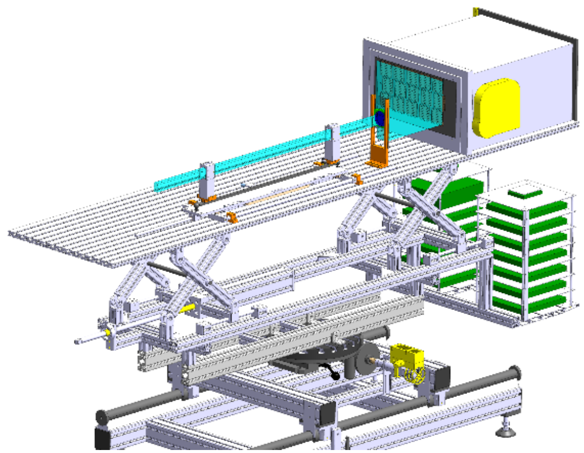


HPDIRC R&D PRIORITIES

FY 22 Plan:

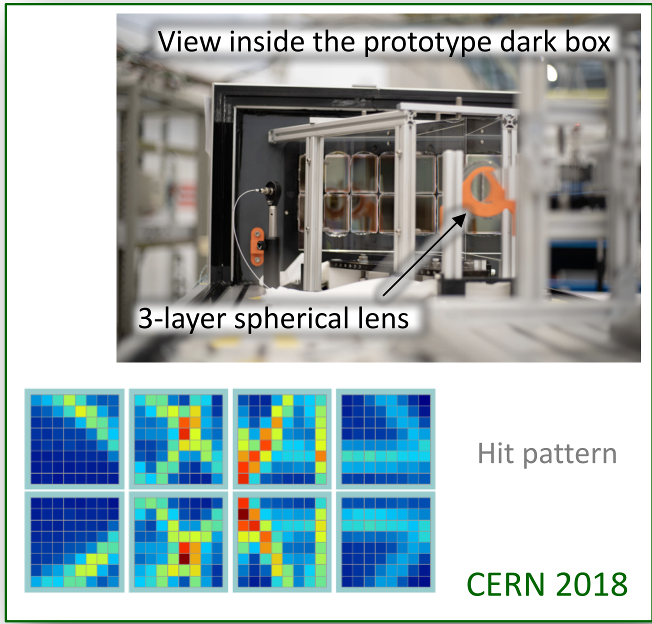
- Cost/Performance optimization of hpDIRC design:
  - Stand alone and full EIC simulation studies
- Incremental development of hpDIRC prototype:
  - Initial prototype with PANDA DIRC optics and readout
  - Development of fast readout electronics
  - Cosmic Ray Telescope setup to develop hpDIRC prototype and integrate readout
  - Procurement of sensors for 2023 test beam
  - Simulation studies for 2023 and 2024 testbeams
- Validation of the BaBar DIRC bar reuse:
  - Finalize and validate disassembly procedure
  - Build and operate QA laser setup

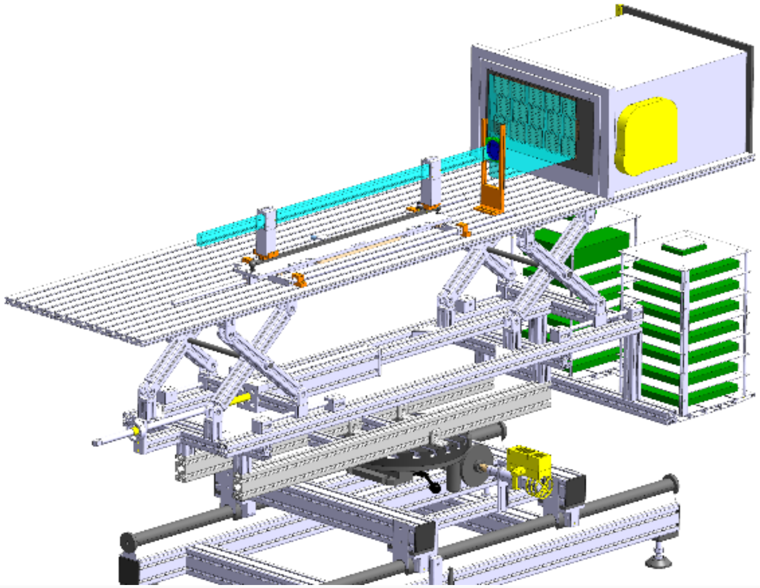




Technical risk: hpDIRC PID design validation

- Resolution and PID performance of system prototype
- PANDA Barrel DIRC prototype tested with particle beams at CERN (2015-18) (included 3-layer spherical lens – but older MCP-PMTs, larger pixels, slower electronics)
- Up to 5 s.d. p/π separation at 7 GeV/c (equivalent to 5.2 s.d. π/K at 3.5 GeV/c)
- Excellent agreement with simulation (same simulation used for hpDIRC)





hpDIRC R&D: Prototype Development

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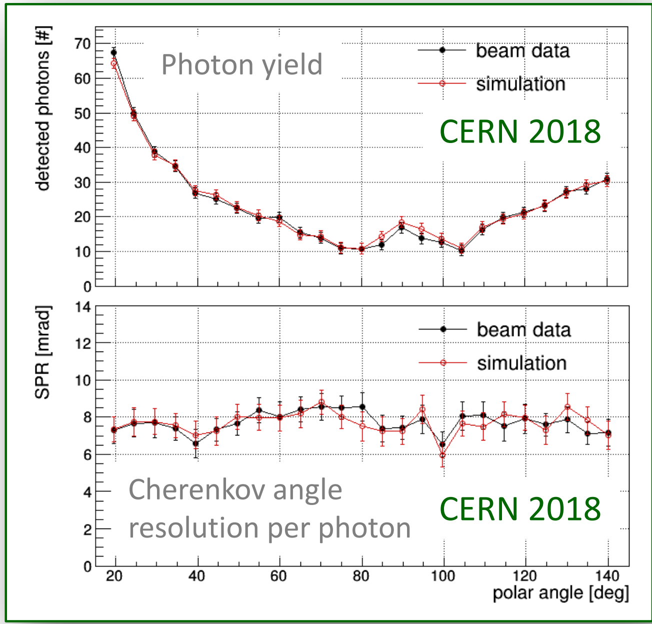
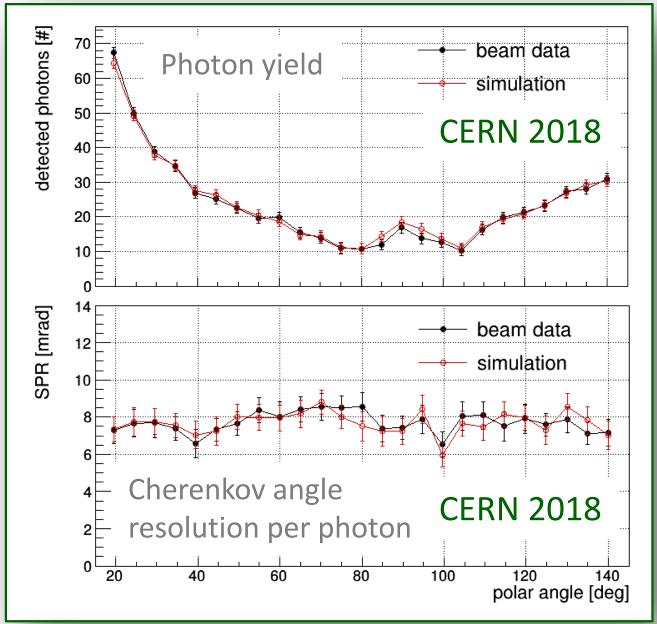


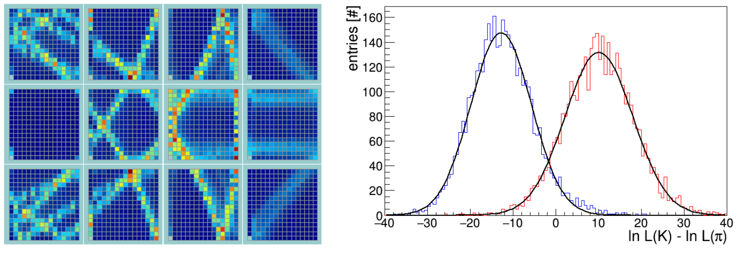
HPDIRC R&D: PROTOTYPE DEVELOPMENT

Technical risk: hpDIRC PID design validation

- Resolution and PID performance of system prototype
- PANDA Barrel DIRC prototype tested with particle beams at CERN (2015-18)
  (included 3-layer spherical lens – but older MCP-PMTs, larger pixels, slower electronics)
- Up to 5 s.d. p/π separation at 7 GeV/c (equivalent to 5.2 s.d. π/K at 3.5 GeV/c)
- Excellent agreement with simulation (same simulation used for hpDIRC)
- Used this simulation to predict PID performance of upgraded prototype
  (new MCP-PMTs and electronics, 3mm pixels, improved PDE, 100ps timing)
- Expected π/K separation at 6 GeV/c at 20°: 3.1 s.d.
- Upgraded PANDA Barrel DIRC prototype (new sensors, new electronics) capable of hpDIRC PID performance validation in particle beams



Geant simulation of upgraded prototype



HPDIRC PROTOTYPE: NUMBER OF PHOTOSENSORS

Example of validated cost/performance optimization, based on simulation study:

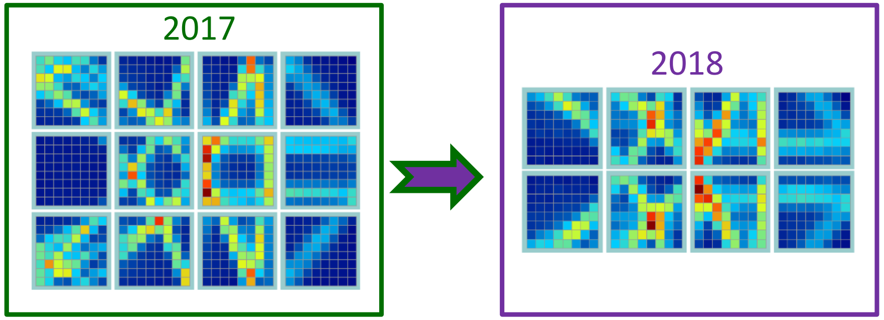
PANDA Barrel DIRC beam test at CERN in 2017 and 2018

2017: prism covered with 12 MCP-PMTs (3x4)

Simulation: 1/3 of the MCP-PMTs can be removed with

no significant impact on PID $\Longrightarrow$ major cost savings.

2018: beam test with reduced coverage to 8 MCP-PMTs (2x4)



accumulated hit pattern

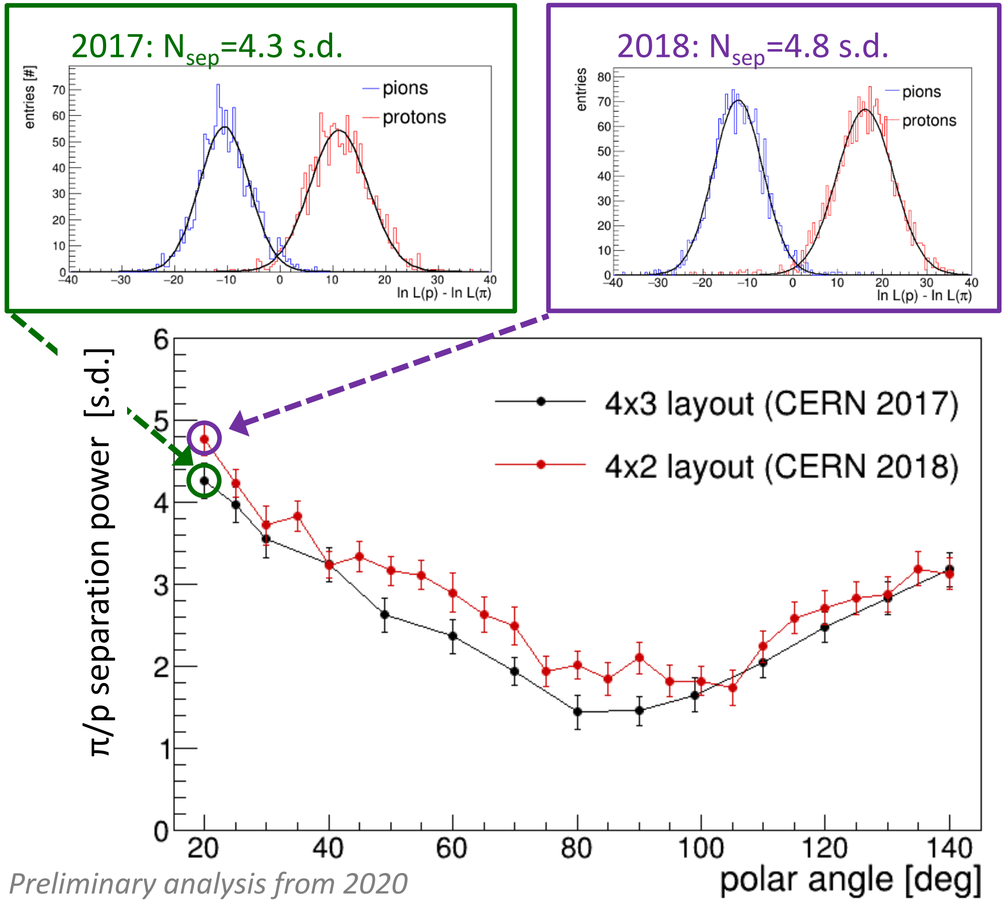
Found expected photon loss rate (30-40%)

with no observable loss of PID performance.

(Small improvement is due to better timing precision in 2018.)

beam data, 7 GeV/c

Note: π/p at 7 GeV/c ≈ π/K at 3.5 GeV/c



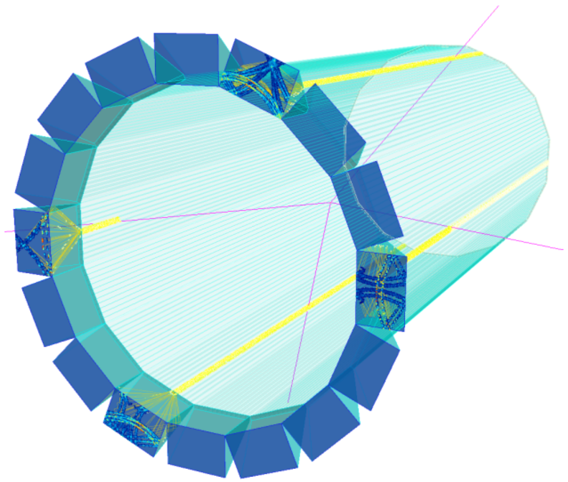
Preliminary analysis from 2020

HPDIRC PROTOTYPE: BARBOX DESIGN

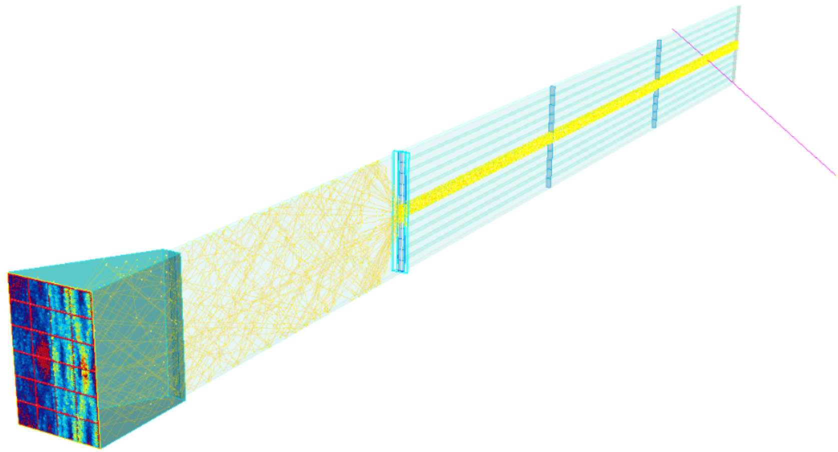
Opportunity: Cost saving and performance improvement

- Narrow radiator bars geometry changed to combination of narrow bars and wide plates as the pre-readout part of barbox
- Hybrid designs can be tested in prototype with no investment in new optics (using PANDA DIRC bar, plate and prism)

GEANT4 visualization of the designs:



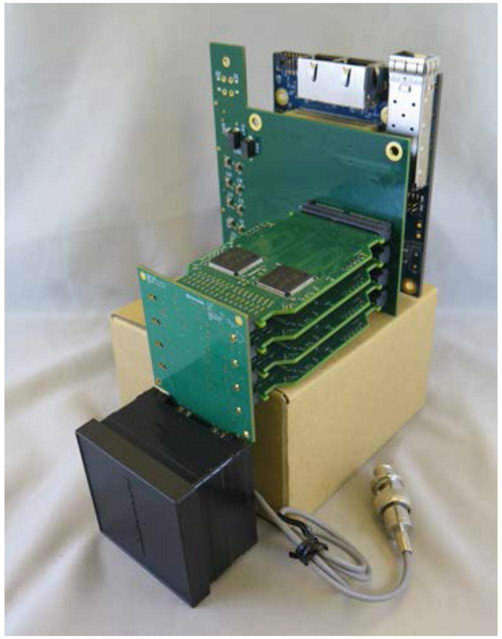
11 narrow bars in each sector



Hybrid of bars and plate in each sector

hpDIRC Prototype: Readout Electronics

hpDIRC's readout unique requirements:



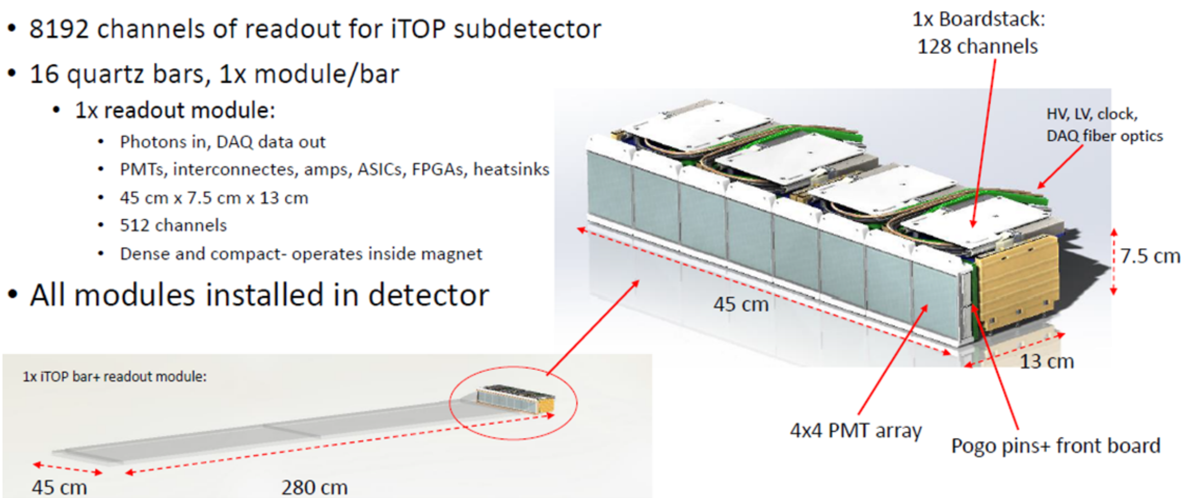
- All three leading candidates for sensors share:
  - High volume of small pixels
  - Fast timing
  - Relatively high rates
- Readout electronics must maintain 60-100ps timing resolution matching sensors
- Performance requirements for e.g. triggerless streaming, data reduction, bandwidth, latency and throughput must be achieved while simultaneously meeting technical requirements for other critical factors such as e.g. power consumption, integration issues at the detector front end along with robust electromechanical sensor interfaces and biasing
- There is **NOTHING** on the market that meets all requirements and scales well
- Test all sensors with minimal effort on electronics and a common readout solution

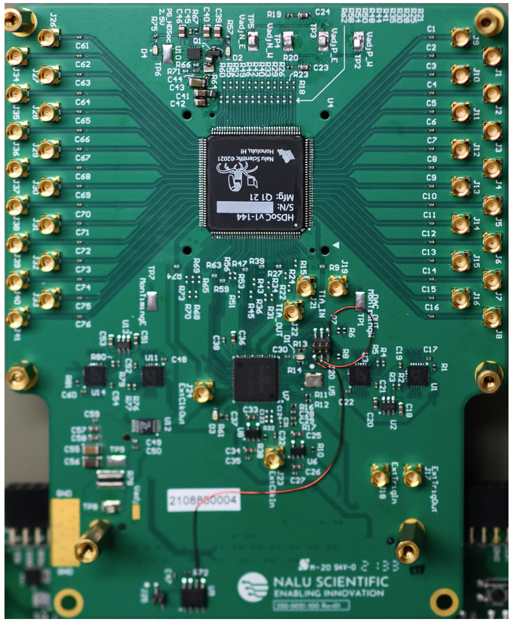
hpDIRC Prototype: Readout Electronics

- The close collaboration between Nalu and UH was established several years ago in the design, fabrication and deployment of the Belle II DIRC TOP detector (below left), which shares many similarities to the hpDIRC. The TOP project was awarded the DOE's Project Management Achievement Award in 2017, and was completed two months ahead of schedule and under budget while meeting or exceeding all objective Key Performance Parameters.

- Nalu's HDSoC ASIC (32-chnl test board below right), currently under development with a DOE Phase II SBIR, is well matched to EIC-PID's performance and technical requirements and the plan is to continue to evolve the platform to systematically address the challenges inherent in ultimately bringing the full EIC detector(s) online and ready for physics data-taking.

- 8192 channels of readout for iTOP subdetector
- 16 quartz bars, 1x module/bar
  - 1x readout module:
    - Photons in, DAQ data out
    - PMTs, interconnectes, amps, ASICs, FPGAs, heatsinks
    - 45 cm x 7.5 cm x 13 cm
    - 512 channels
    - Dense and compact- operates inside magnet
- All modules installed in detector





hpDIRC Prototype: Readout Electronics

➢ **SCHEDULE MATCHING hpDIRC TIMELINE!**

FY22- Develop and de-risk electronics

- ➢ Use 32ch HDSoC eval card as a building block to readout a subset of channels of various sensors (Photonis, HRPPD, Photek…)
- ➢ Nalu will provide 32 ch HDSoC eval board+engineering knowhow and FW/SW customization
- ➢ UH will provide post-doc and lab for testing and data analysis - prepare for cosmic telescope testing (for 32 or 64ch)
- ➢ Nalu will develop and fab the <u>64 channel HDSoC</u> using Phase II SBIR funds
- ➢ Preliminary design for a modular integrated readout solution.

FY’23 - Prepare for summer ’23 beam tests

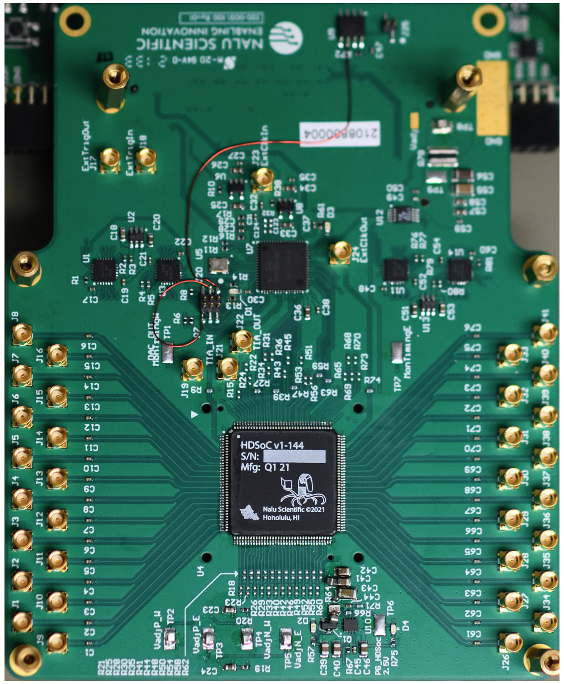
- ➢ Design and fab sensor specific 4-6k channel electro-mechanically integrated readout based on 64ch HDSoC (with design reuse in mind) and prepare for beam tests - contingent on proper budget allocation and prompt start on day one of FY23.
- ➢ Perform beam tests, analyze data and present results
- ➢ Perform a study on ASIC customization for various subdetectors (SBIR funds slightly more generic R&D than detector specific work).

FY’24-25- ASIC and electronic customization

- ➢ Customize HDSoC for speed (60ps resolution), data rates, processing capacity of each detector.
- ➢ Fab, package, test and qualify - rather low risk given underlying ASIC is mature
- ➢ Design high channel count subdetectors using customized ASICs.

FY’26-27 - Mass production

- ➢ Design for cost, dedicated ASIC fab and packaging.
- ➢ Board level designs tweaked for cost and sent to contract fab/assy houses
- ➢ Calibration, qualification, installation.



HPDIRC PROTOTYPE: DEVELOPMENT AND VALIDATION

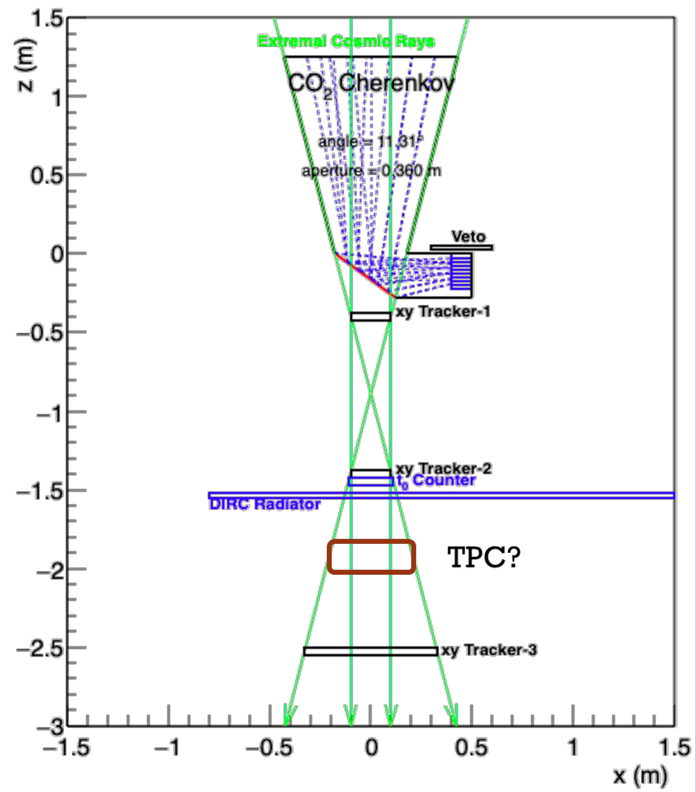
Oportunity: Preparation of Tests of DIRC Prototype with Cosmic Rays

- Crowded beam test schedules – validate hpDIRC with cosmic muons
- Work on mechanical and readout aspects of hpDIRC prototype
- Collaboration of CUA – GSI – ODU – SBU to develop cosmic ray telescope (CRT) design and measurement plan

Current design:

- Momentum selection: new CO_2 Cherenkov threshold tagger (> ~3.5 GeV/c)
- 3D tracking: two GEM tracker stations (from sPHENIX) above and below DIRC bar, potentially combined with TPC prototype
- Shower rejection: scintillator plates as veto counters
- T_0 start counter: MCP-PMT/LAPPD or mRPC or PICOSEC-Micromegas counter
- Mechanical design progressing, prototype polar angle rotation foreseen
- Geant simulation package in preparation

Plan to start measurements in summer 2022



Work in collaboration with SBU team
A. Deshpande, K. Dehmelt, T. Hemmick, S. Park

BaBar DIRC Bars Disassembly

Technical risk/financial opportunity: reuse of BaBar DIRC bars

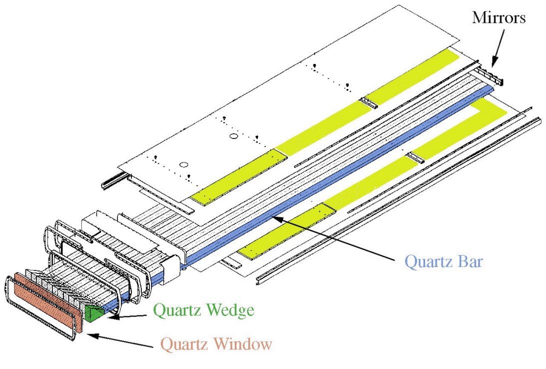
- BaBar DIRC disassembled in 2010, SLAC/DOE made DIRC bars available for reuse
- Save cost, reduce technical and schedule risk related to fabrication of new bars
- Eight bar boxes located at SLAC, awarded to JLab for potential use in EIC

  Four unmodified bar boxes at JLab for GlueX DIRC since 2018
- Full-size bar boxes are too long, do not fit into EIC central detector,

  wedges deteriorate resolution: need to disassemble bar boxes for reuse
- Twelve bar boxes: 576 bars (each 17 x 35 x 1200 mm^3), sufficient number for EIC

  (even 8 bar boxes may be enough if bars can be extracted with good quality and excellent yield)
- In contact with SLAC BaBar experts and JLab, discussed procedure for disassembly of bar box and decoupling of bars from wedge and other bars using heat gun approach
- R&D is required to finalize and validate procedure and to assess cost and technical risk

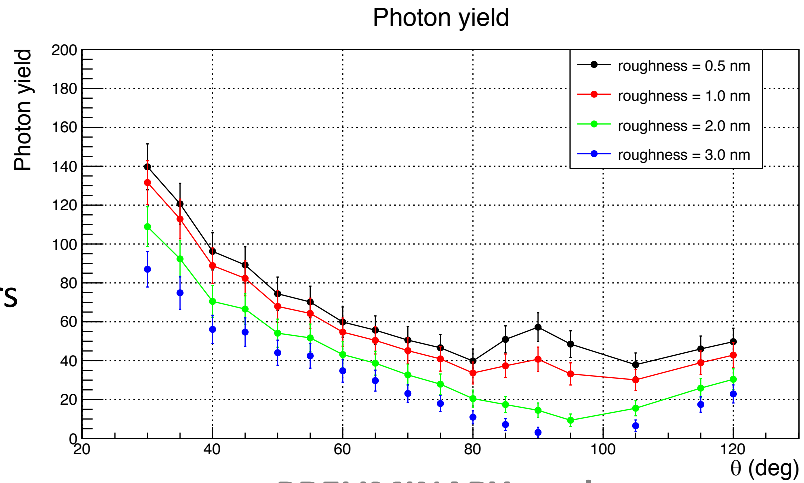
  (Optical quality? Yield? DIRC clean room at Jlab or ODU? Funding (manpower, tooling, SLAC labor, travel)? Is additional cutting/polishing required to refinish ends and/or reduce bar length?)



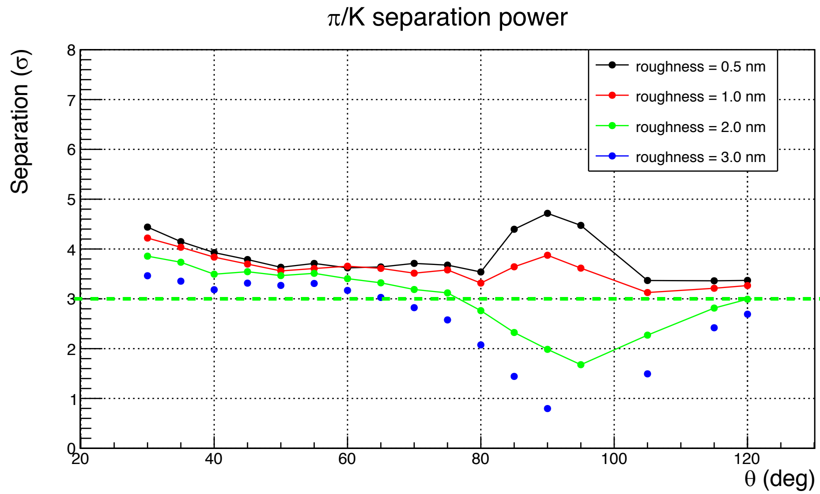
QA of Disassembled Bars

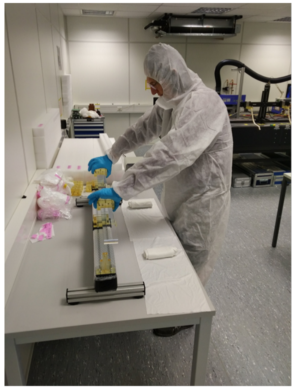
Technical risk: QA of the disassembled bars in laser setup:

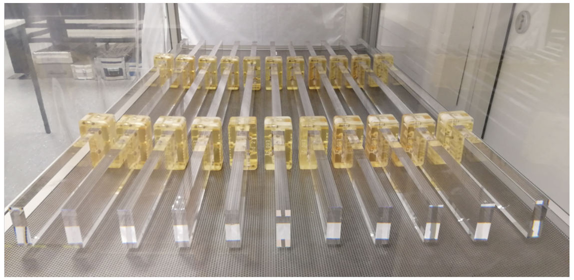
- BaBar DIRC bars were produced with 0.3-0.5nm surface optical finish
- Drop in optical quality can cause photon yield and performance drop
- If first disassembled bars will match original quality, ~10% of remaining bars will be tested

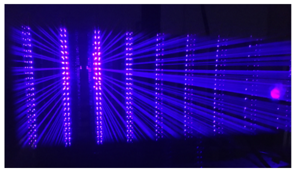


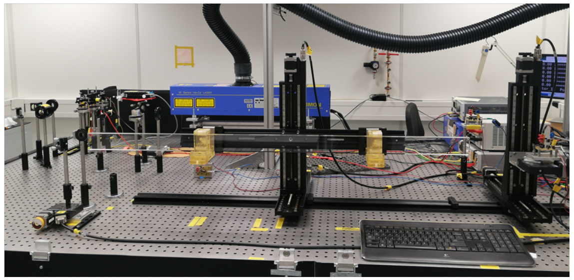
PRELIMINARY study











hpDIRC Summary and Budget Request

FY 22 Plan:

Budget request:

- hpDIRC Cost/Performance design optimization ⟹ Extend PostDoc contract
- Incremental development of hpDIRC prototype:
  - Assembly and operation of CRT setup ⟹ Travel for CUA, Materials for SBU
  - Initial prototype with PANDA DIRC readout ⟹ Materials and travel for CUA, GSI
  - Development of fast readout electronics ⟹ PostDoc and Materials for UH
  - Procurement of Sensors ⟹ Sensors for FY23 testbeam
- Reuse of BaBar DIRC bars validation ⟹ Materials, PostDoc for ODU

Item	Institution	Requested
Postdoc,50%	CUA	$80k
QA of BaBar DIRC bars	CUA	$50k
Prototype Evaluation at CRT	CUA	$20k
Prototype Equipment	CUA	$10k
Sensors for 2023 EIC hpDIRC Prototype (CUA)	CUA	$140k
Travel	CUA/GSI	$10k
Postdoc, 50%	ODU	$80k
CRT readout electronics	SBU	$20k
CRT materials	SBU	$15k
Postdoc, 50%	UH	$60k
Test-bench/readout board assembly	UH	$15k
ASIC and engineering support	Nalu	$25k
Total		$525k

HPDIRC SUMMARY AND BUDGET REQUEST

Item	Institution	Requested
Postdoc,50%	CUA	$80k
QA of BaBar DIRC bars	CUA	$50k
Prototype Evaluation at CRT	CUA	$20k
Prototype Equipment	CUA	$10k
Sensors for 2023 EIC hpDIRC Prototype (CUA)	CUA	$140k
Travel	CUA/GSI	$10k
Postdoc, 50%	ODU	$80k
CRT readout electronics	SBU	$20k
CRT materials	SBU	$15k
Postdoc, 50%	UH	$60k
Test-bench/readout board assembly	UH	$15k
ASIC and engineering support	Nalu	$25k
Total		$525k

Institution	CUA	ODU	SBU	UH	Nalu	**Total**
Requested	$310k	$80k	$35k	$75k	$25k	$525k

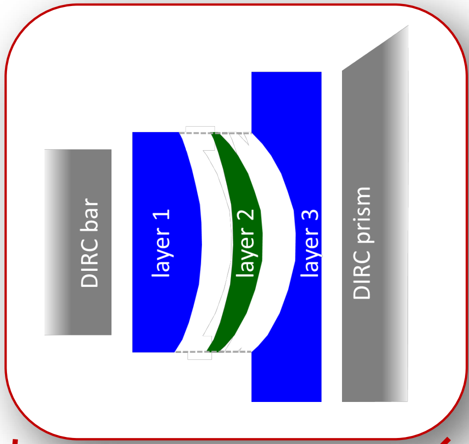
Extra Material

Technical risk: hpDIRC PID design validation

- Radiation hardness and focusing performance of 3-layer lens

Conventional plano-convex lens with air gap limits DIRC performance

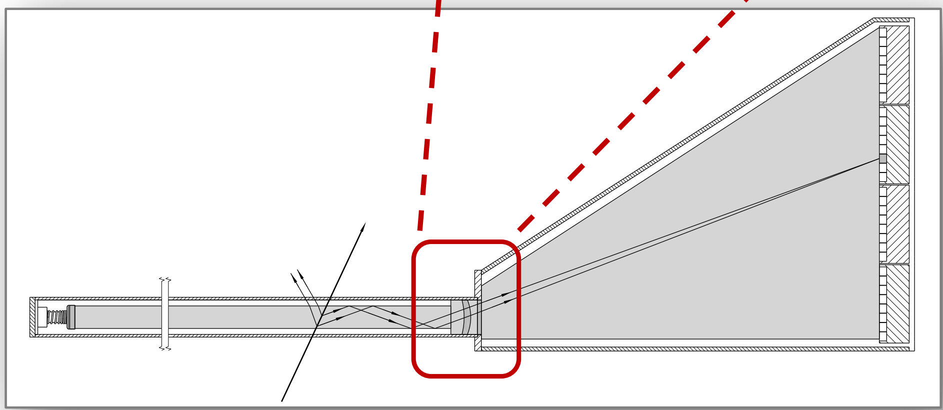
- Significant photon yield loss for particle polar angles around 90°, gap in DIRC PID
- Distortion of image plane, PID performance deterioration



Key element of hpDIRC design:

- 3-layer compound lens (without air gap):

layer of high-refractive index material (focusing/defocusing)
sandwiched between two layers of fused silica



- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Successfully produced prototype lenses and validated performance in PANDA Barrel DIRC prototype with particle beams at CERN and GSI

Technical risk: hpDIRC PID design validation

- Radiation hardness and focusing performance of 3-layer lens

Conventional plano-convex lens with air gap limits DIRC performance

- Significant photon yield loss for particle polar angles around 90°
- Distortion of image plane for photons with steeper propagation angles

Key element of hpDIRC design:

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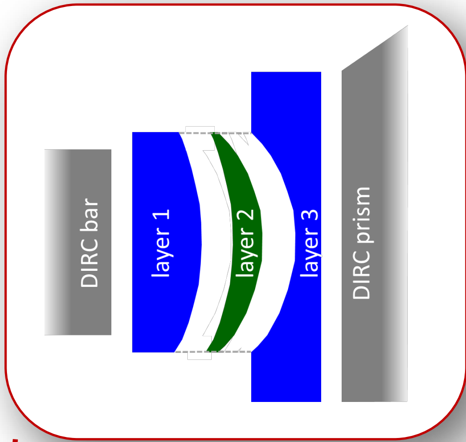
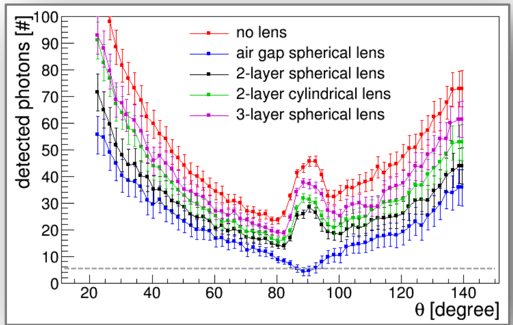
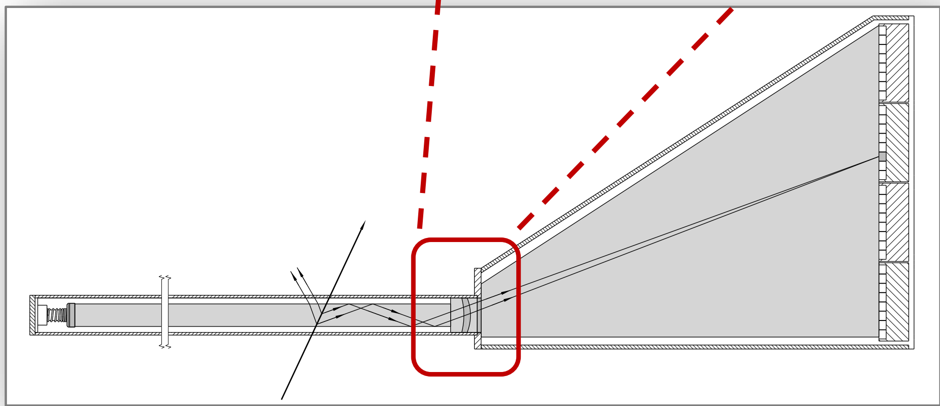






Source:
PANDA Barrel DIRC TDR
doi:10.1088/1361-6471/aade3d

HPDIRC R&D PRIORITIES / FY21 HIGHLIGHTS

Technical risk: hpDIRC PID design validation

- Radiation hardness and focusing performance of 3-layer lens

Conventional plano-convex lens with air gap limits DIRC performance

- Significant photon yield loss for particle polar angles around 90°
- Distortion of image plane for photons with steeper propagation angles

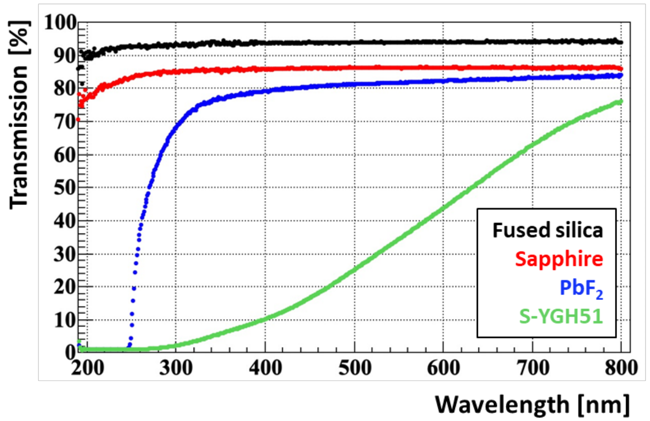
Key element of hpDIRC design:

- 3-layer compound lens (without air gap):
  layer of high-refractive index material (focusing/defocusing)
  sandwiched between two layers of fused silica

hpDIRC R&D activities:

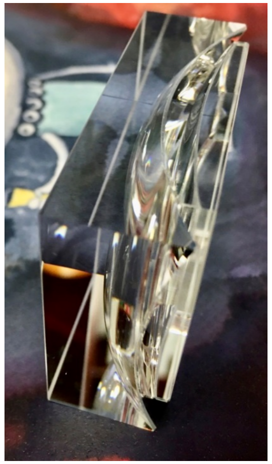
- Identify radiation hard material for middle layer (^{60}Co completed, neutrons next)
- Demonstrate that rad-hard material is suitable for lens fabrication by industry (prototype lenses produced, ready for tests)
- Validate focusing properties/flat focal plane → upgraded laser setup at ODU

Transmission after 2Mrad dose (^{60}Co source)



Work supported by Jim Kierstead (BNL)

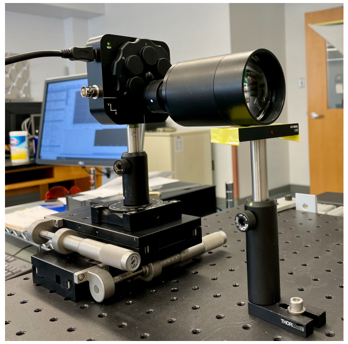
Sapphire (RMI, USA)



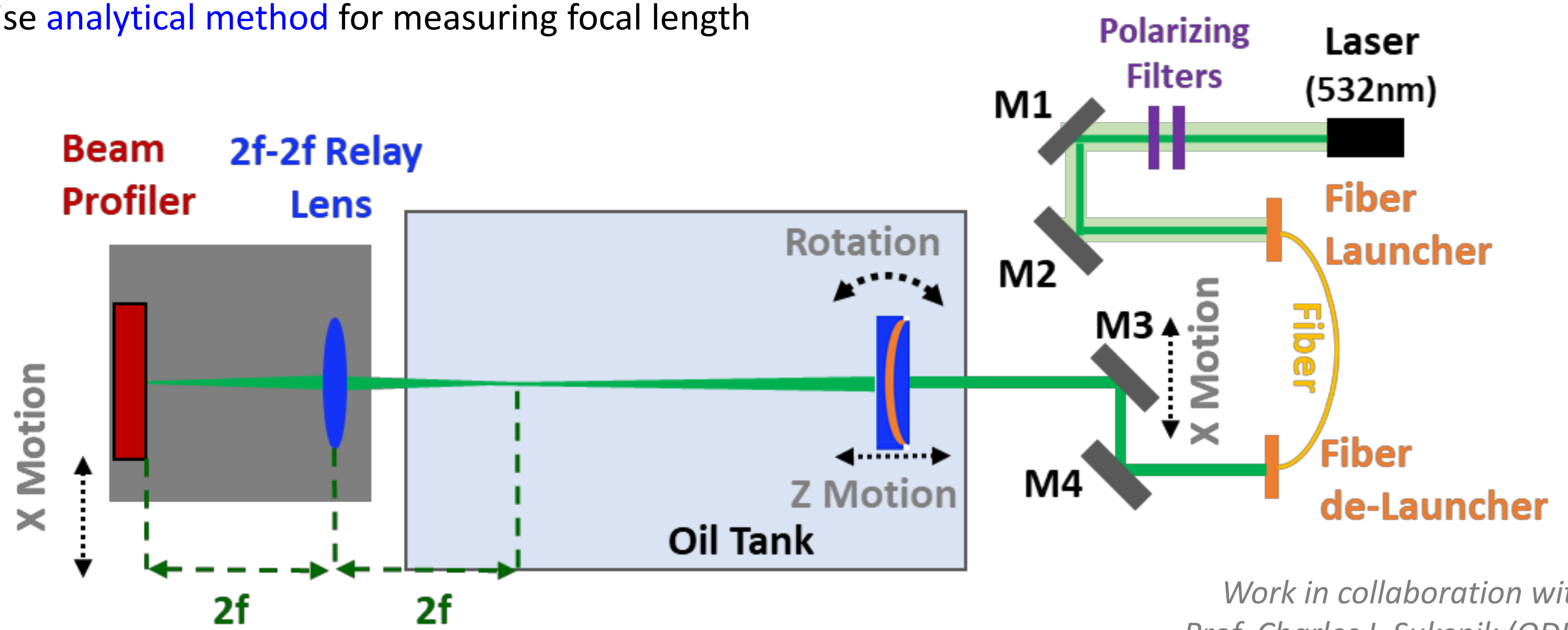
PbF$_2$ (HIT, China)

Received in FY21

Upgrade of laser setup at ODU



- Setup for evaluation of the shape of the focal plane of prototype lenses
- Completed upgrade: heavier mechanical support, laser fiber launcher, 2f-2f relay lens, CCD camera beam profiler with commercial software
- Better quality of laser beam, more repeatable positioning, faster and more precise analytical method for measuring focal length



Work in collaboration with Prof. Charles I. Sukenik (ODU)

HPDIRC R&D PRIORITIES / FY21 HIGHLIGHTS

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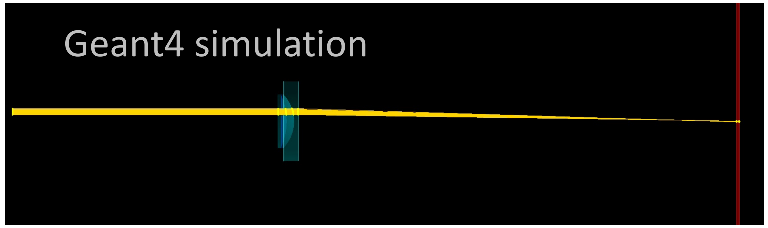

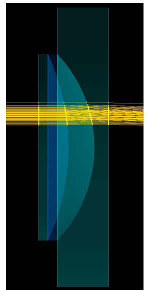

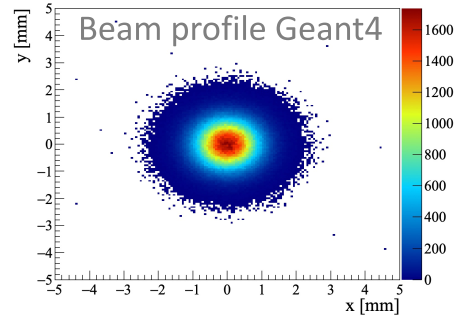

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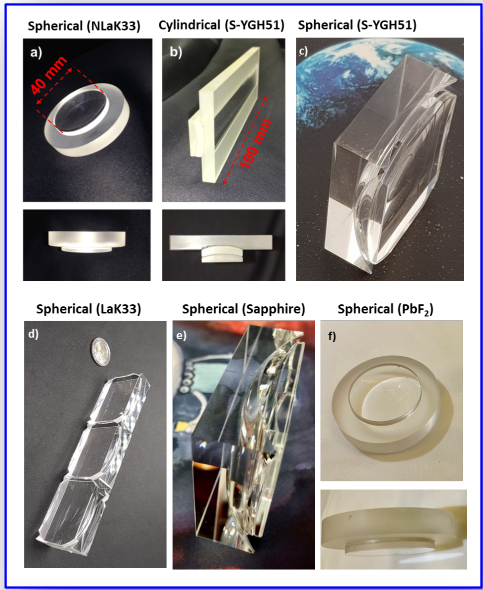
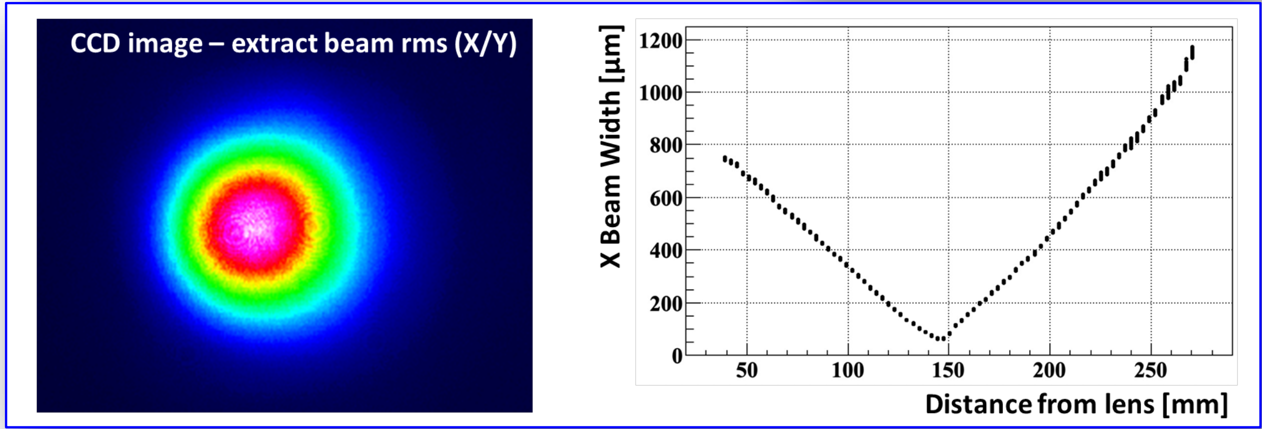
- Better quality of laser beam, more repeatable positioning, faster and more precise analytical method for measuring focal length
- Developed Geant simulation of setup – improve understanding of aberrations
- Calibration complete, lens scans started
- Several compound lens prototypes available





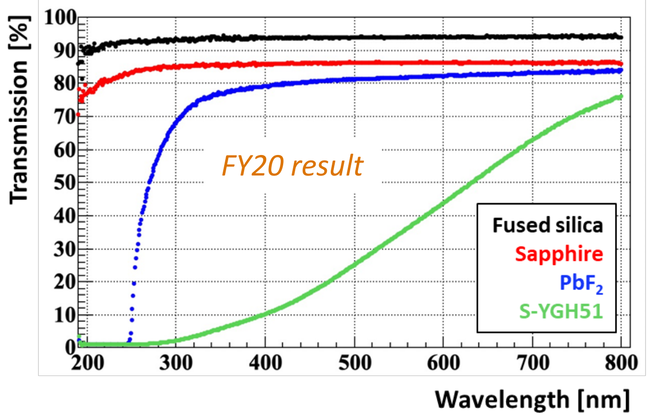
HPDIRC R&D PRIORITIES / FY21 HIGHLIGHTS

Technical risk: hpDIRC PID design validation

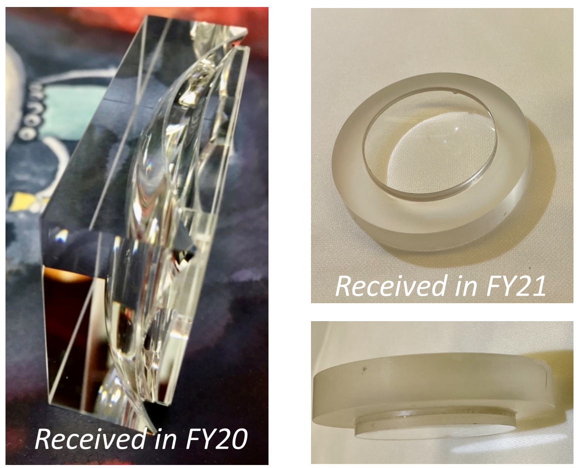
- Radiation hardness and focusing performance of 3-layer lens

hpDIRC R&D activities:

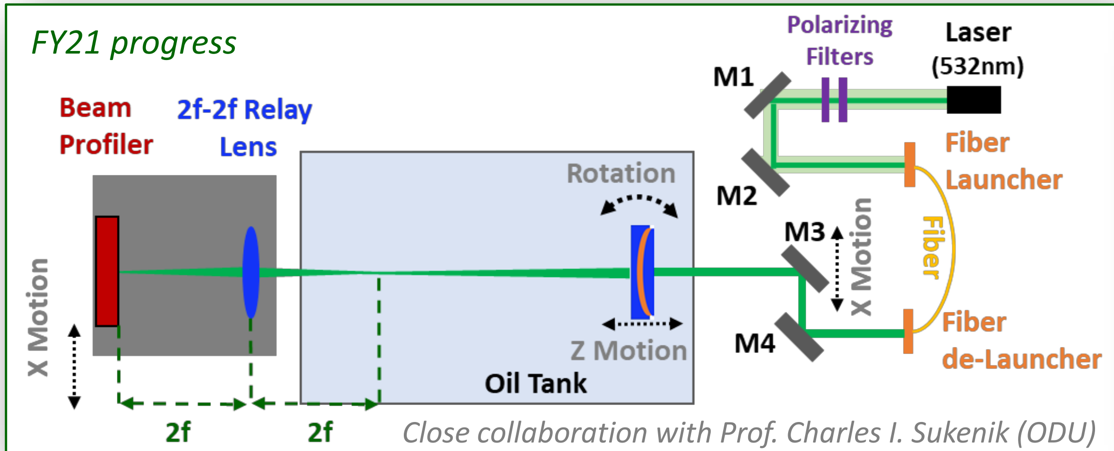
- Identify radiation-hard material for middle layer (^{60}Co study complete, neutrons next)
- Demonstrate that rad-hard material is suitable for lens fabrication by industry
  (New sapphire and PbF_2 lens prototypes produced, ready for tests)
- Validate focusing properties/flat focal plane
  → completed upgrade of laser setup at ODU in FY21, starting lens scans



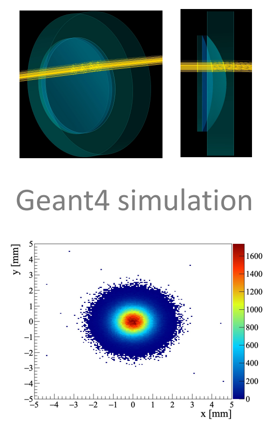
Work supported by Jim Kierstead (BNL)



FY21 progress



Close collaboration with Prof. Charles I. Sukenik (ODU)



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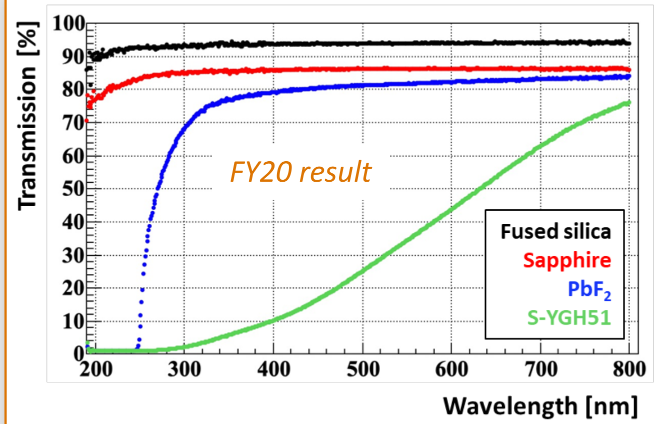
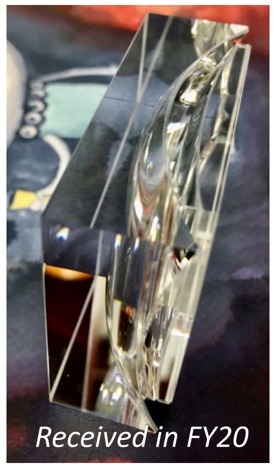
Transmission after 2Mrad dose (^{60}Co source)

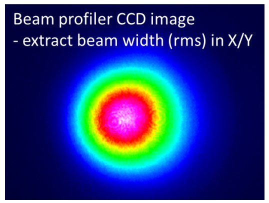


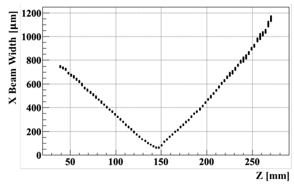
Work supported by Jim Kierstead (BNL)

Sapphire (RMI, USA) **PbF_2 (HIT, China)**



FY21 progress

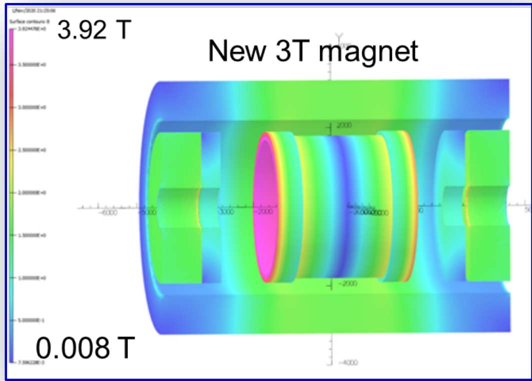




HPDIRC R&D PRIORITIES

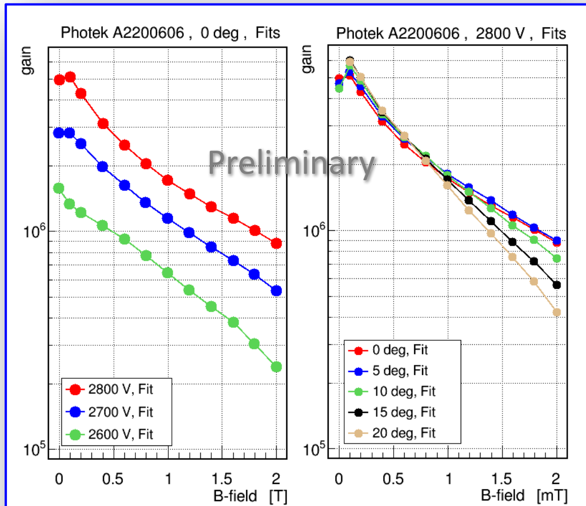
Technical risk: photon sensor performance in 3 Tesla magnet

- Some of the detector proposals plan to use a new 3 T magnet, other proposals favor magnets with 1.5—2 Tesla fields
- Waiting for field maps for proposed new 3 Tesla magnet (EIC@IP6) to determine local field strength and direction at location of DIRC sensors



Y. Furletova, IR2@EIC workshop, March 2021

- Ongoing effort within eRD14, studying LAPPD/commercial MCP-PMT in high B-fields
- Small-pore MCP-PMTs shown to be OK for fields up to 2 Tesla
  (see recent result from A. Lehmann et al. for 6µm-pore 2'' Photek AuraTek MCP-PMT)



A. Lehmann et al, shown by J. Milnes, IEEE NSS, Nov. 2020

- If expected fields are much higher: investigate SiPM as alternative
  (dark noise, radiation damage, cooling, annealing, integration issues)

HPDIRC R&D PRIORITIES

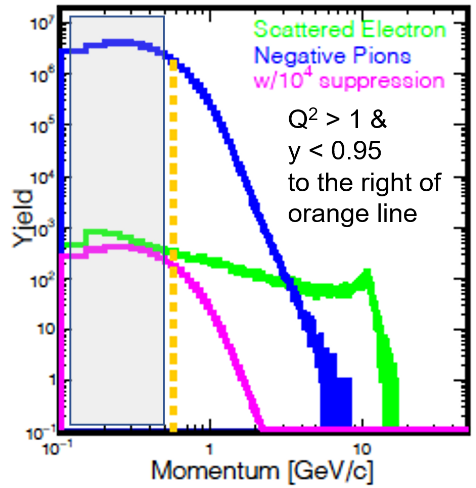
Performance opportunity: improve e/π separation at low momentum

- Yellow report effort identified need for supplemental e/π suppression from PID systems to support EM calorimeter at lower momentum
- Simulation shows that ID of scattered electron requires $\mathcal{O}(10^4)$ suppression of large pionic background

- Started simulation effort, multiple scattering limits hpDIRC performance
- Recent result, without special measures: > 3 s.d. e/π separation at 1.2 GeV/c (caveat: long non-Gaussian tails)
- Even "out-of-the-box" hpDIRC capable of very useful background suppression

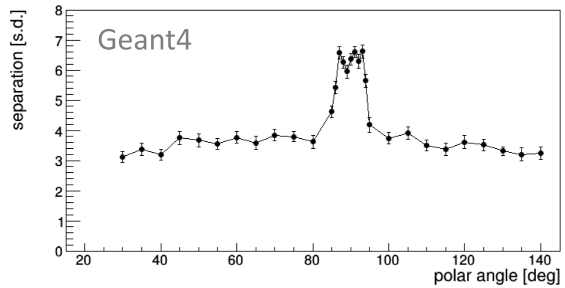
- Better performance possible, study use of post-DIRC tracking, "ring center fit", optimized DIRC geometry (bar width/thickness, bar/plate hybrid), etc.
- Post-DIRC tracking expected to further improve π/K separation at high momentum

-1.0 < η < 0.0 (half of DIRC Barrel)



Simulation by B. Schmookler

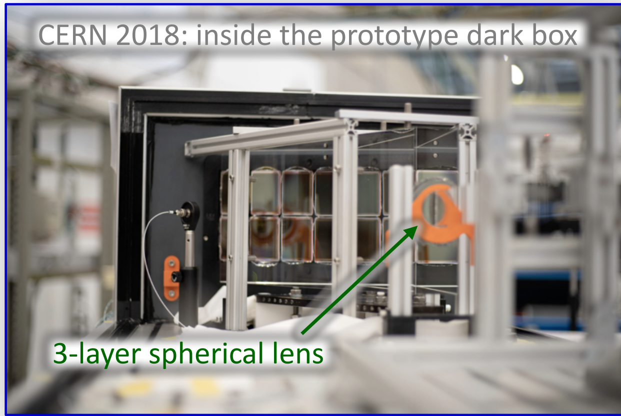
hpDIRC e/π separation at 1.2 GeV/c momentum



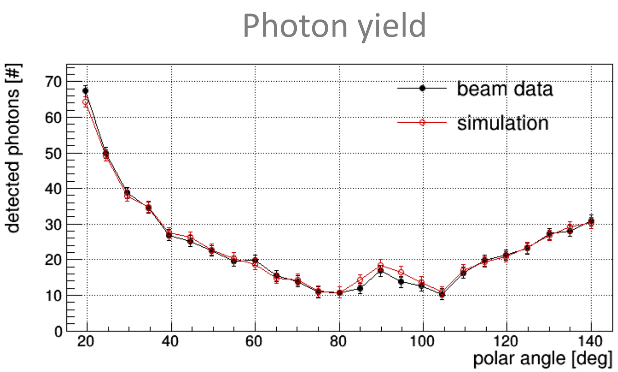
HPDIRC R&D PRIORITIES

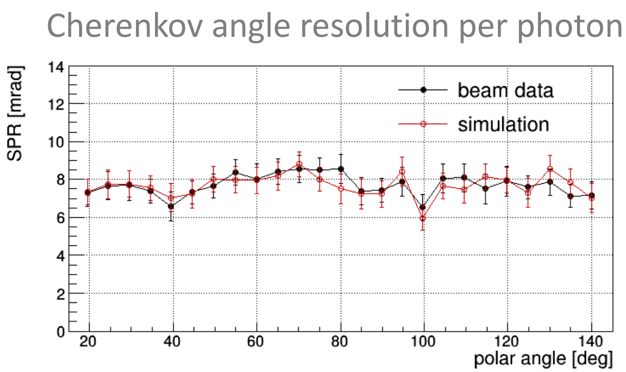
Technical risk: hpDIRC PID design validation

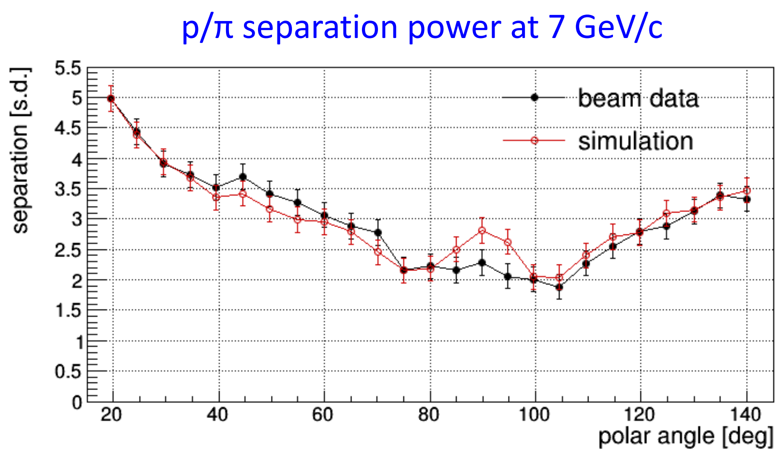
- Resolution and PID performance of system prototype
- PANDA Barrel DIRC prototype tested with particle beams at CERN (2015-18)
  (included 3-layer spherical lens – but older MCP-PMTs, larger pixels, slower electronics)
- Recently optimized event selection and analysis procedure for CERN 2018 data
  (in preparation for upcoming journal publication)
- Achieved 5 s.d. p/π separation at 7 GeV/c, excellent agreement with simulation



CERN 2018







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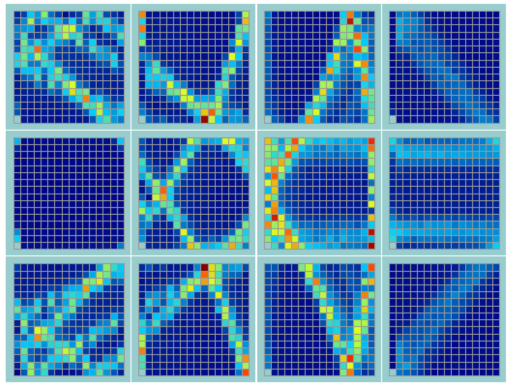
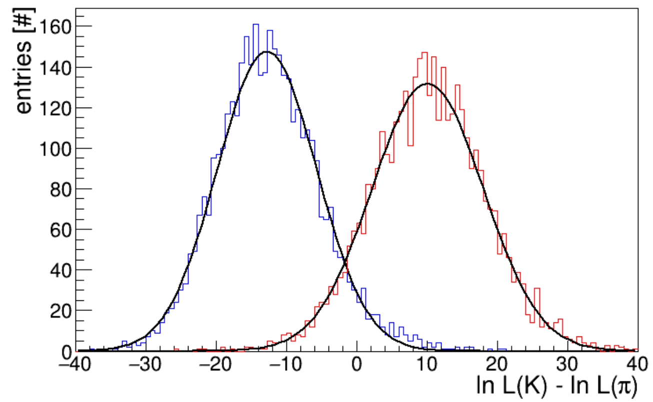
- Recently optimized event selection and analysis procedure for CERN 2018 data
  (in preparation for upcoming journal publication)
- Achieved 5 s.d. p/π separation at 7 GeV/c, excellent agreement with simulation
- Used this simulation to predict performance for upgraded prototype
  - Assumed replacement of older Planacon MCP-PMTs with current commercial MCP-PMTs (3x3mm^2 pixels, improved PDE)
  - Assumed improved single photon timing (100ps rms)
- Predicted π/K separation at 6 GeV/c at 20°: 3.1 s.d.
- Upgraded PANDA Barrel DIRC prototype (new sensors, new electronics) capable of hpDIRC PID performance validation in particle beams

Accumulated hit pattern
for upgraded prototype (Geant4)



π/K separation at 6 GeV/c at 20°: 3.1 s.d.
for upgraded prototype (Geant4)



BACKUP SLIDES

eRD14 – EIC PID consortium

An integrated program for particle identification (PID)
for a future Electron-Ion Collider (EIC) detector

A suite of detector systems covering the full angular- and momentum range required for an EIC detector

- Different technologies in different parts of the detector
- Focus on hadron ID with an electron ID capability

A cost-effective sensor and electronics solution

- Development and testing of photosensors (to satisfy EIC requirements)
- Development of readout electronics needed for prototyping

Consortium synergies (including reduction of overall R&D costs)

- Close collaboration within the consortium, with coordinated goals and timelines (*e.g.*, DIRC & LAPPD, mRICH & dRICH, sensors and readout for prototype tests, etc).
- Strong synergies with non-EIC experiments and R&D programs (PANDA, CLAS12, GlueX, PHENIX, commercial LAPPDs) result in large savings.

Slide from P. Nadel-Turonski,
R&D Committee Meeting,
BNL, July 2019

eRD14 – EIC PID consortium

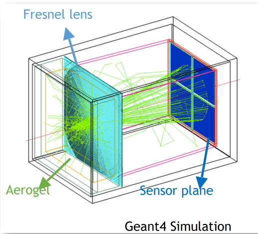
An integrated program for particle identification (PID)

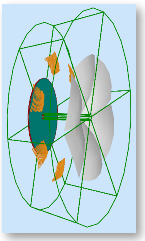
for a future Electron-Ion Collider (EIC) detector

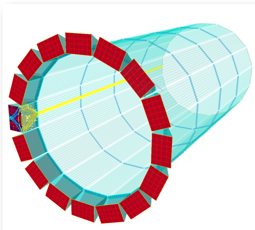
M. Alfred[1], P. Antonioli[32], W. Armstrong[11], B. Azmoun[2], F. Barbosa[3], L. Barion[8], W. Brooks[4], T. Cao[5], P. Chao[11], M. Chiosso[33], M. Chiu[2], E. Cisbani[6,7], M. Contalbrigo[8], S. Danagoulian[9], M.D. Da Rocha Rolo[33], A. Datta[10], A. Del Dotto[6], A. Denisov[13], J.M. Durham[14], A. Durum[13], R. Dzhygadlo[15], C. Fanelli[3,16], D. Fields[10], Y. Furletova[3], C. Gleason[18], M. Grosse-Perdekamp[19], J. Harris[20], M. Hattawy[21], X. He[22], H. van Hecke[14], T. Horn[23], J. Huang[2], C. Hyde[20], Y. Ilieva[24], S. Joosten[11], G. Kalicy[23], A. Kebede[9], B. Kim[25], J. Kim[11], E. Kistenev[2], A. Lehmann[29], M. Liu[14], R. Majka[20], J. McKisson[3], R. Mendez[4], M. Mirazita[34], I. Mostafanezhad[26,31], A. Movsisyan[8], P. Nadel-Turonski[12], M. Patsyuk[30], K. Peters[15], R. Pisani[2], R. Preghenella[32], W. Roh[22], P. Rossi[3], M. Sarsour[22], C. Schwarz[15], J. Schwiening[15], C.L. da Silva[16], N. Smirnov[20], J. Stevens[28], A. Sukhanov[2], X. Sun[22], S. Syed[22], R. Towell[10], Sh. Tripathi[26], C. Tuve[35], G. Varner[26], R. Wagner[11], N. Wickramaarachchi[23], C.-P. Wong[22], J. Xie[11], Z.W. Zhao[17], B. Zihlmann[3], C. Zorn[3]

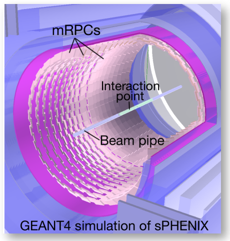
Contacts: P. Nadel-Turonski, Y. Ilieva

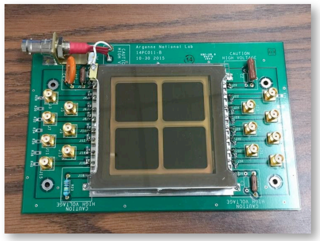
[1]Howard University, [2]Brookhaven National Lab, [3]Jefferson Lab, [4]Universidad Tecnica Federico Santa Mara, Chile, [5]University of New Hampshire, [6]INFN, Sezione di Roma, Italy, [7]Istituto Superiore di Sanita, Italy, [8]INFN, Sezione di Ferrara, Italy, [9]North Carolina A&T State University, [10]University of New Mexico, [11]Argonne National Lab, [12]Stony Brook University, [13]Institute for High Energy Physics, Russia, [14]Los Alamos National Lab, [15]GSI, Germany, [16]Laboratory for Nuclear Science, Massachusetts Institute of Technology, [17]Duke University, [18]Indiana University, [19]University of Illinois, [20]Yale University, [21]Old Dominion University, [22]Georgia State University, [23]Catholic University of America, [24]University of South Carolina, [25]City College of New York, [26]University of Hawaii, [27]Abilene Christian University, [28]College of William & Mary, [29]Friedrich Alexander Universität Erlangen-Nürnberg, Germany, [30]Joint Institute for Nuclear Research, Russia, [31]Nalu Scientific, Honolulu, [32]INFN, Sezione di Bologna, Italy, [33]INFN, Sezione di Torino, Italy, [34]INFN, Sezione di Frascati, Italy, [35]INFN, Sezione di Catania, Italy

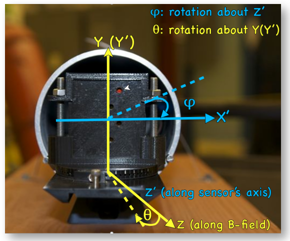


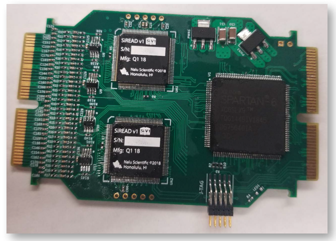








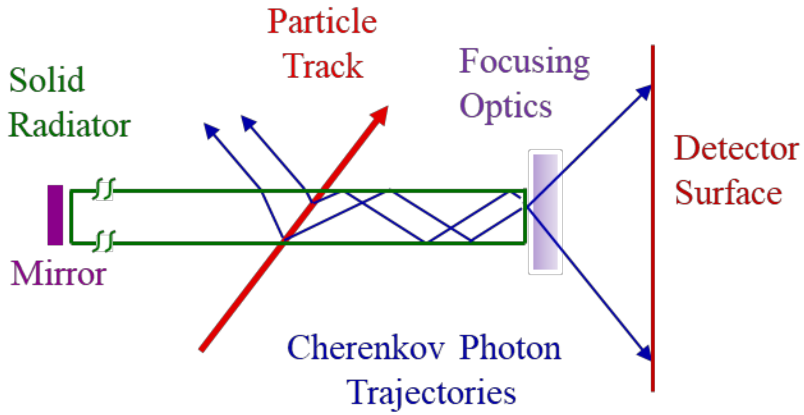




General DIRC Topics

DIRC CONCEPT

- Charged particle traversing radiator with refractive index n with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos\theta_c = 1/\beta n(\lambda)$.

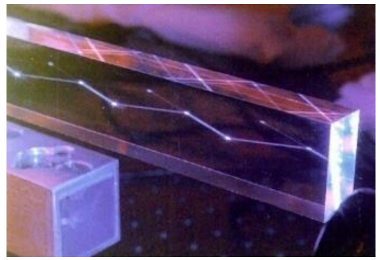


- For $n>\sqrt{2}$ some photons are always totally internally reflected for $\beta\approx 1$ tracks.

- Radiator and light guide: bar, plate, or disk made from Synthetic Fused Silica ("Quartz") or fused quartz or acrylic glass or …

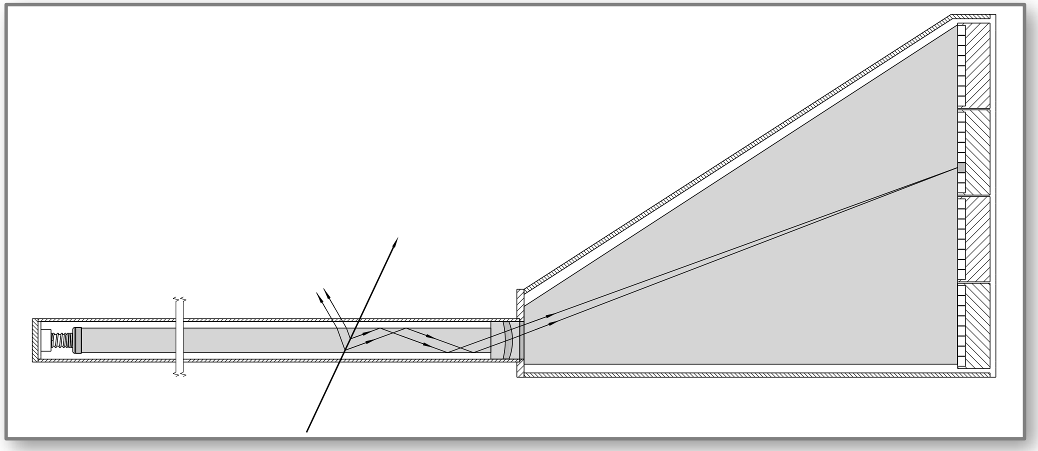
- Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)

→ Major technological challenge for BaBar – is it really possible to efficiently and precisely conserve angle during up to 2000 reflections? ... and maintain that surface quality for 10+ years?



DIRC Concept

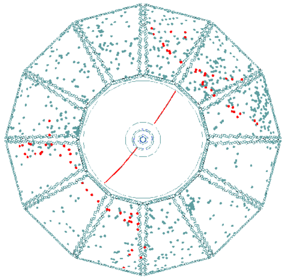
- Mirror attached to one bar end, reflects photon back to readout end.
- Photons exit radiator via optional focusing optics into expansion region, detected on photon detector array.
- DIRC is intrinsically a 3-D device, measuring: x, y, and time of Cherenkov photons, defining θ_c, ϕ_c, $t_{propagation}$.
- Ultimate deliverable for DIRC: PID likelihoods.



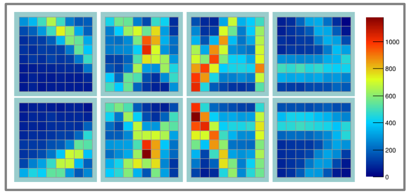
DIRC hit patterns are not typical Cherenkov rings.

Different DIRCs use different reconstruction approaches to provide likelihood for observed hit pattern (in detector space or in Cherenkov space) to be produced by e/μ/π/K/p plus event/track background.

DIRC requires momentum and position of particle measured by tracking system.

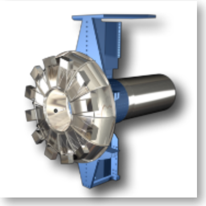
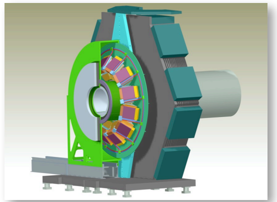
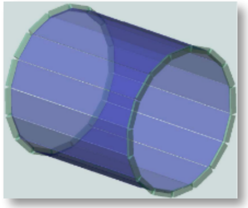
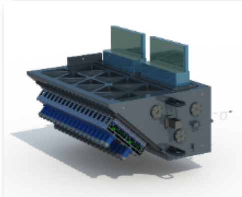
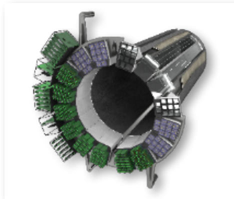
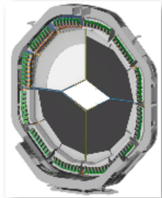
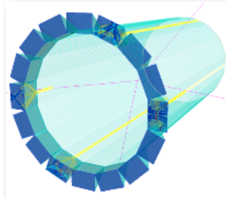


Typical event
BaBar DIRC



Accumulated hit pattern
PANDA Barrel DIRC

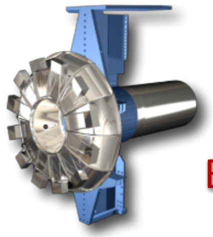
DIRC Concept

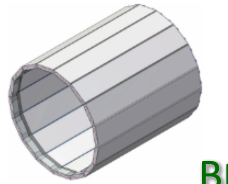
Detection of Internally Reflected Cherenkov Light

- DIRC counters have become a popular solution for hadronic PID over the past two decades.
- DIRCs are radially very compact, providing more space for calorimeters or tracking detectors.
- BaBar DIRC was the first DIRC, PID in barrel region, very successful, π/K up to ~4 GeV/c (1999-2008).
- Prompted DIRC interest by several experiments: Belle II, SuperB, PANDA, GlueX, and others;
  R&D to make DIRC readout more compact, expand momentum reach, use for endcap PID.
  Key technology: multi-pixels sensors, small pixels, fast timing, tolerance of high rates and B fields.
- Very active and complex R&D, applying advances in sensors, electronics, imaging, algorithms.

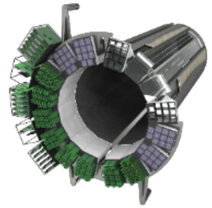
BARREL DIRC COUNTERS



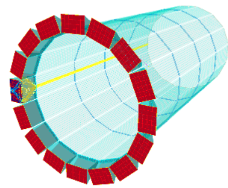
BABAR DIRC



BELLE II TOP



PANDA BARREL DIRC



EIC HPDIRC*

Radiator geometry	Narrow bars *(35mm)*	Wide plates *(450mm)*	Narrow bars *(53mm)*	Narrow bars *(35mm)*
Barrel radius	85cm	115cm	48cm	100cm
Bar length	490cm *(4×122.5cm)*	250cm *(2×125cm)*	240cm *(2×120cm)*	420cm *(4×105cm)*
Number of long bars	144 *(12×12 bars)*	16 *(16×1 plates)*	48 *(16×3 bars)*	176 *(16×11 bars)*
Expansion volume	110cm, ultrapure water	10cm, fused silica	30cm, fused silica	30cm, fused silica
Focusing	None (pinhole)	Mirror (for some photons)	Spherical lens system	Spherical lens system
Photodetector	~11k PMTs	~8k MCP-PMT pixels	~8k MCP-PMT pixels	~100k MCP-PMT pixels
Timing resolution	~1.5ns	<0.1ns	~0.1ns	~0.1ns
Pixel size	25mm diameter	5.6mm×5.6mm	6.5mm×6.5mm	3.2mm×3.2mm
PID goal	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 3.5 GeV/c	3 s.d. π/K to 6 GeV/c
Timeline	1999 - 2008	Installed 2016	Installation 2024/25	TDR-ready in 2024

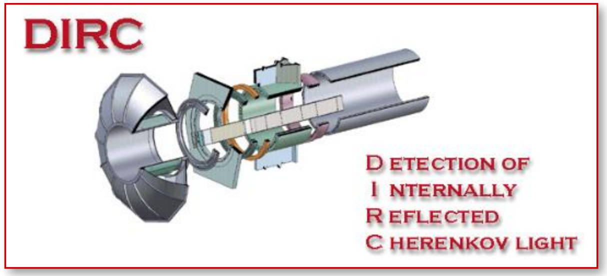
****Initial generic design***

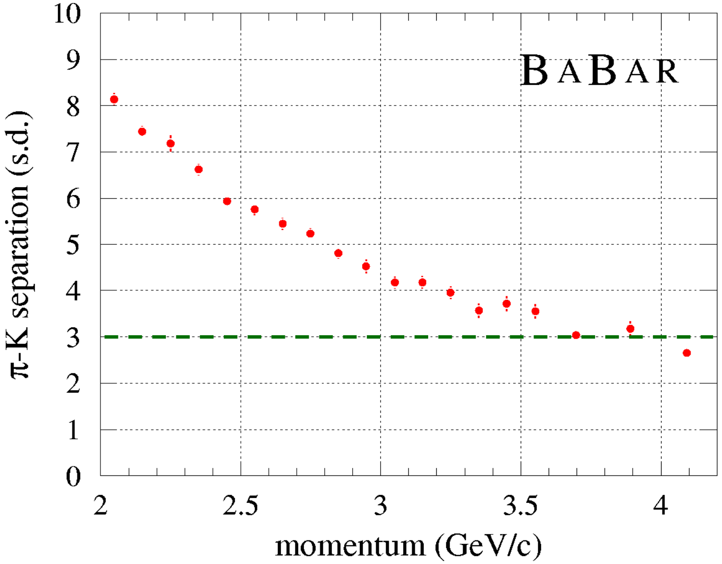
DIRC Resolution

I. Adam et al., Nucl. Instr. Meth. A, 538, 2005.

$$\sigma^2_{\theta_c}(particle) = \sigma^2_{\theta_c}(photon) / N_\gamma + \sigma^2_{correlated}$$

$\sigma_{\theta_c}(particle)$	Cherenkov angle resolution per particle
$\sigma_{\theta_c}(photon)$	Cherenkov angle resolution per photon (bar size, pixel size, chromatic, bar imperfections)
N_γ	Number of detected photons per particle (bar size, bar imperfections, Photon Detection Efficiency)
$\sigma_{correlated}$	Contribution from external sources (tracking, multiple scattering, etc.)



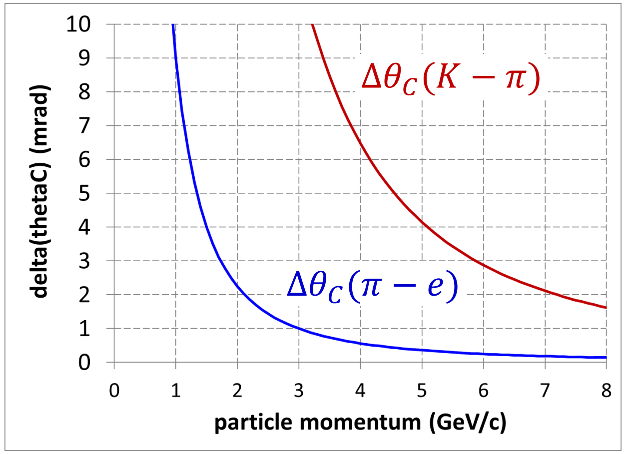


BaBar DIRC achieved 2. 4 mrad θ_C resolution at 3-4 GeV/c,

3 s.d. π/K separation at 4 GeV/c

How can we push this performance to higher momentum?

Improving on the BaBar DIRC



PID performance largely driven by track Cherenkov angle (θ_C) resolution.

Required resolution defined by refractive index of radiator.

Example: π/K separation in synthetic fused silica <n>≈1.473

→ 2.9 mrad π/K difference in θ_C at 6 GeV/c;

→ need ~1 mrad resolution per particle for 3 s.d. separation.

Approach:

Smaller track angular error (better tracking detector)

Higher photon yield (modern sensors with better PDE)

Improve Cherenkov angle resolution per photon

BABAR-DIRC Cherenkov angle resolution: 9.6 mrad per photon, 2.4 mrad per particle

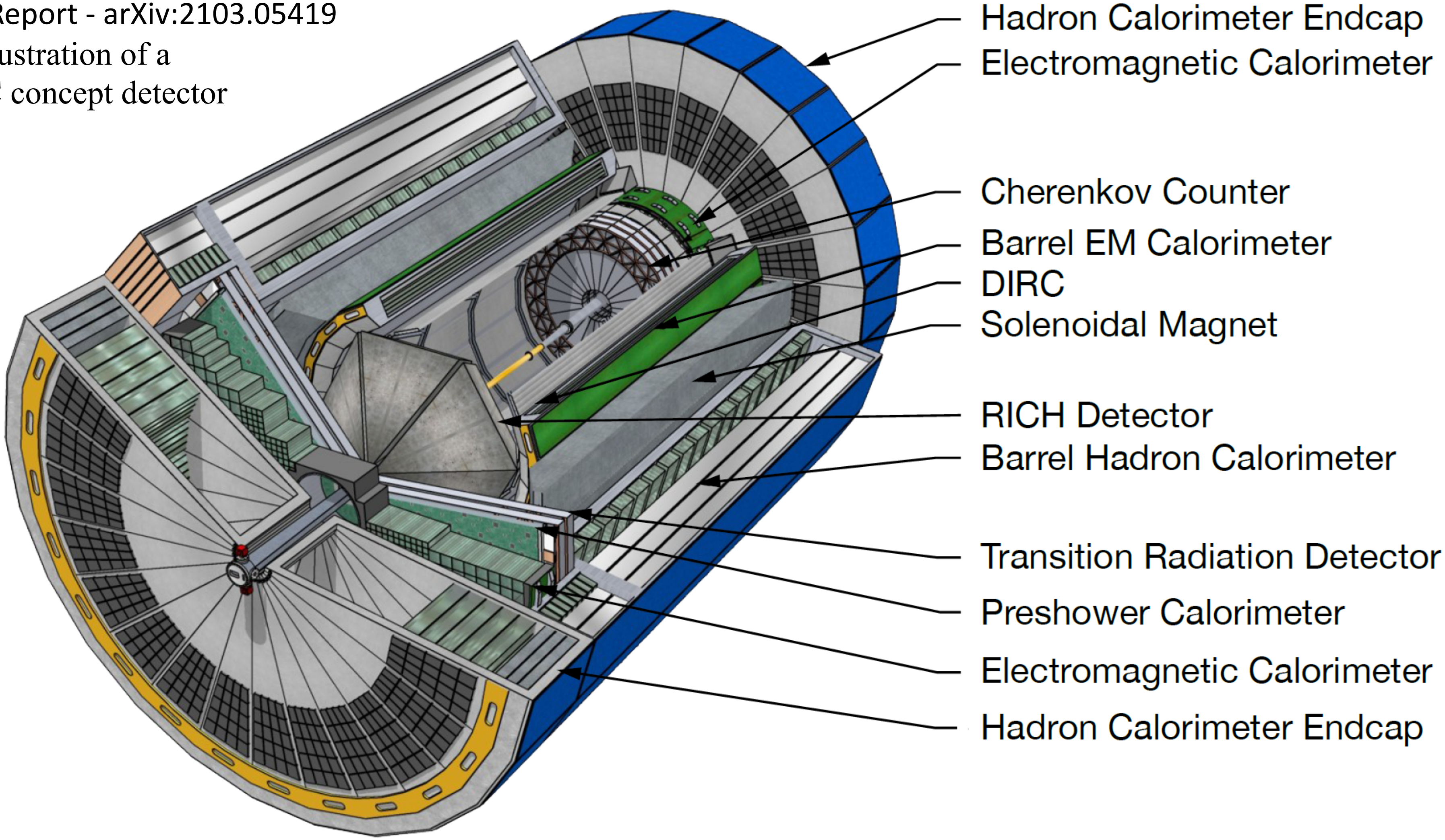
Limited in BABAR by:			Improve for future DIRCs via:
▪ size of bar image	~4.1 mrad	→	▪ focusing optics
▪ size of PMT pixel	~5.5 mrad	→	▪ smaller pixel size
▪ chromaticity (n=n(λ))	~5.4 mrad	→	▪ better time resolution
	9.6 mrad	→	5-7 mrad per photon → 1 mrad per particle

SuperB, Belle II, PANDA & EIC

EIC DIRC

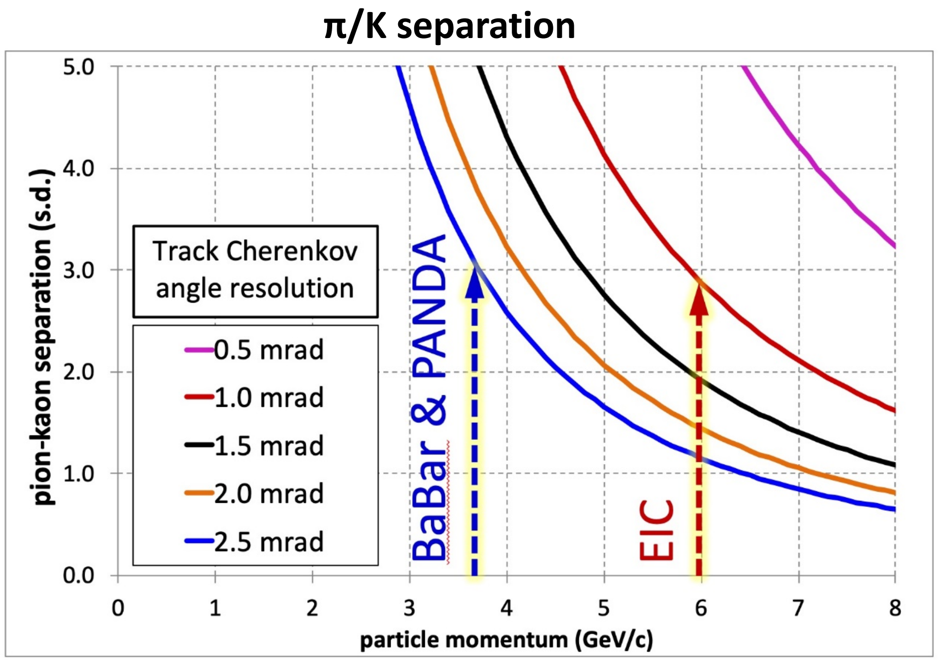
EIC Yellow Report - arXiv:2103.05419

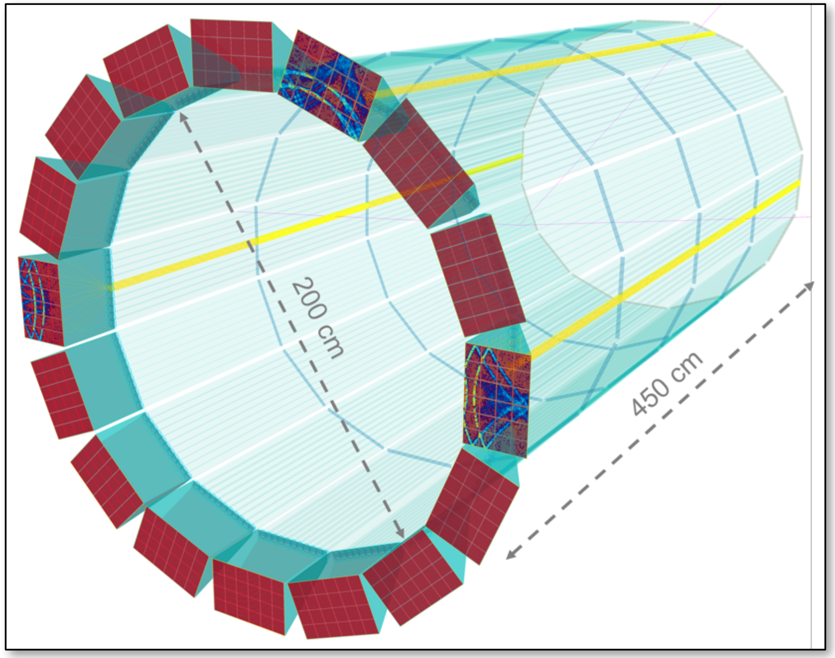
Cutaway illustration of a generic EIC concept detector



hpDIRC Performance Goal

hpDIRC: a high-performance DIRC counter for radially compact hadronic PID in the barrel region of the future EIC experiments

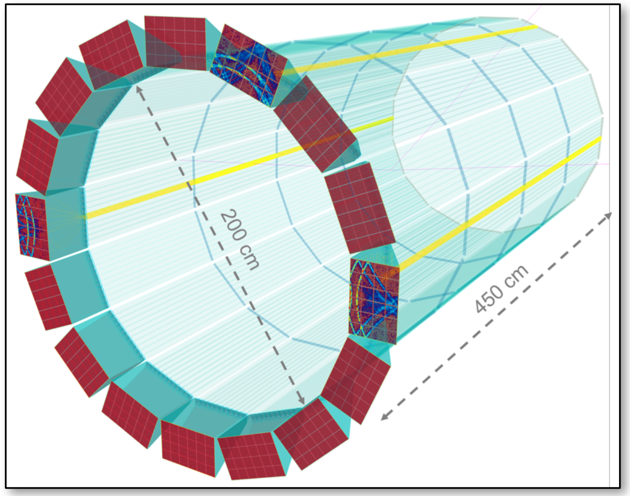


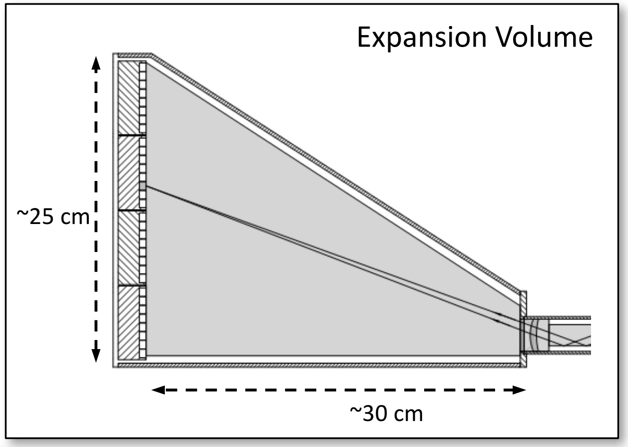


EIC High-Performance DIRC (hpDIRC)

Expected performance: ≥ 3 s.d. π/K separation up to 6 GeV/c

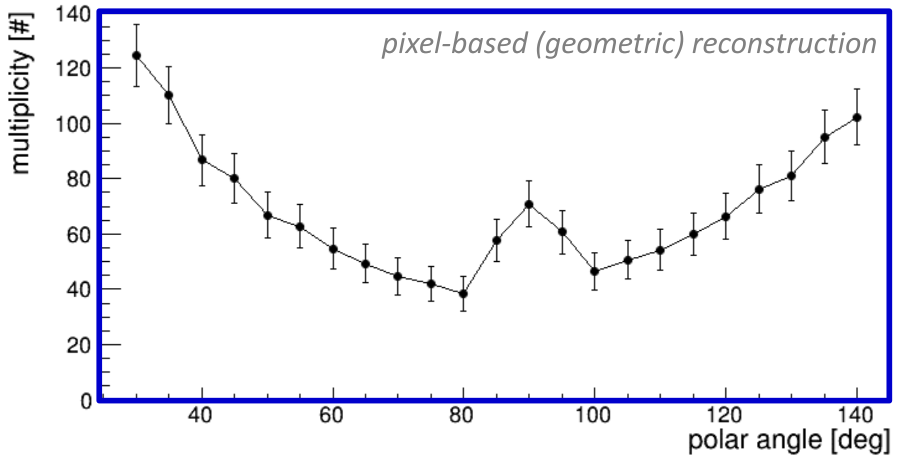
- Generic reference design:
  16 sectors, one bar box and one expansion volume per sector
- Focusing optics:
  Radiation-hard 3-layer spherical lens
- Expansion volume:
  Solid fused silica prism: 24 x 36 x 30 cm^3 (H x W x L)
  Additional longitudinal space for MCP-PMTs, readout cards, cables: ~20cm
- Number of sectors, barrel radius and bar length can be optimized for integration, PID performance largely independent of barrel radius and bar length
- Expansion volume shape can be optimized for MCP-PMT magnetic field performance (tilted backplane) but length is directly related to performance



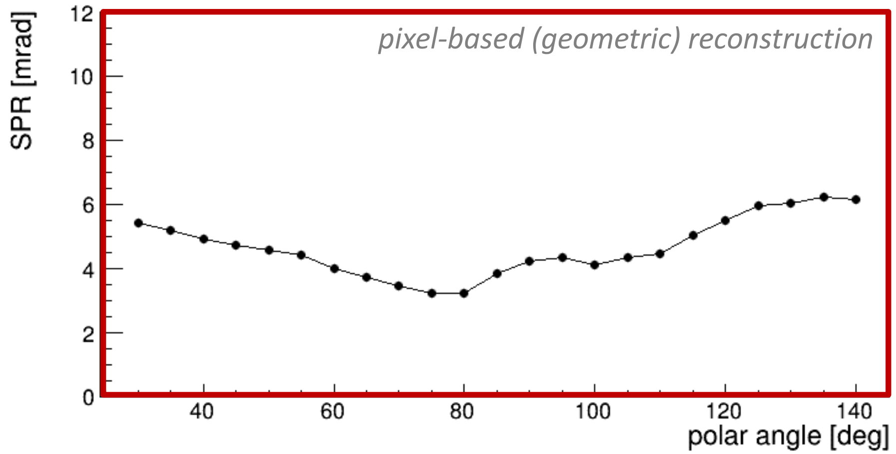


HPDIRC PERFORMANCE IN GEANT4

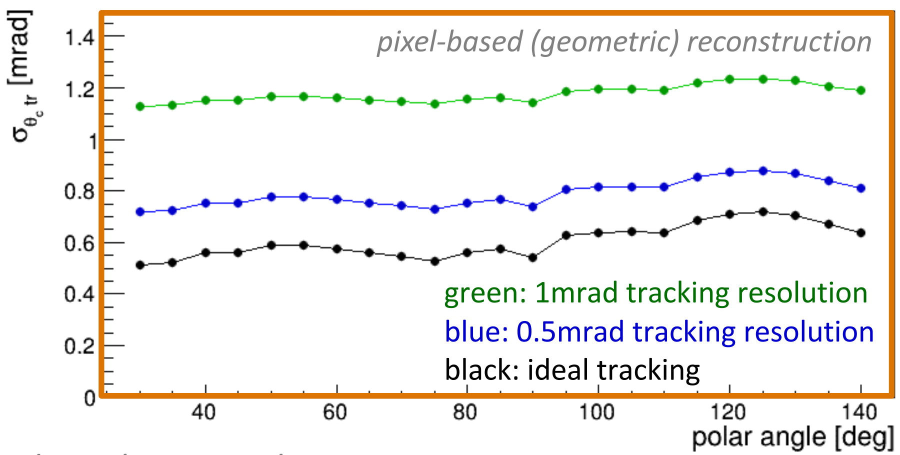
Photon yield per particle



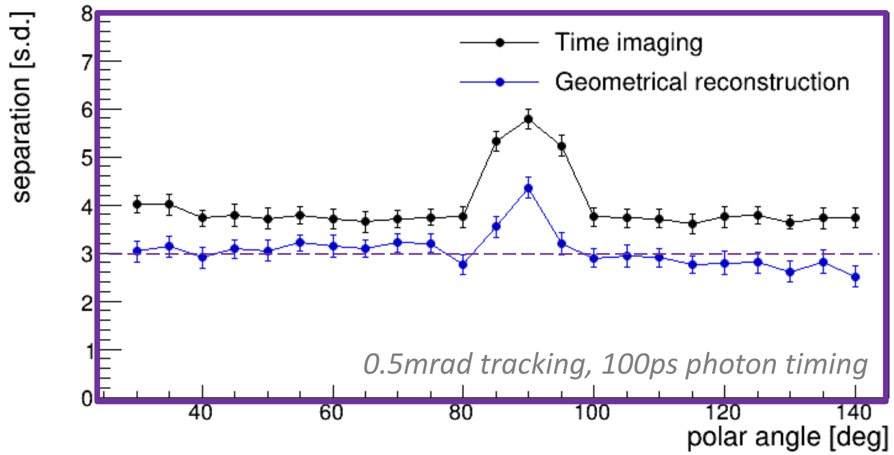
Cherenkov angle resolution per photon (SPR)



Cherenkov angle resolution angle per particle

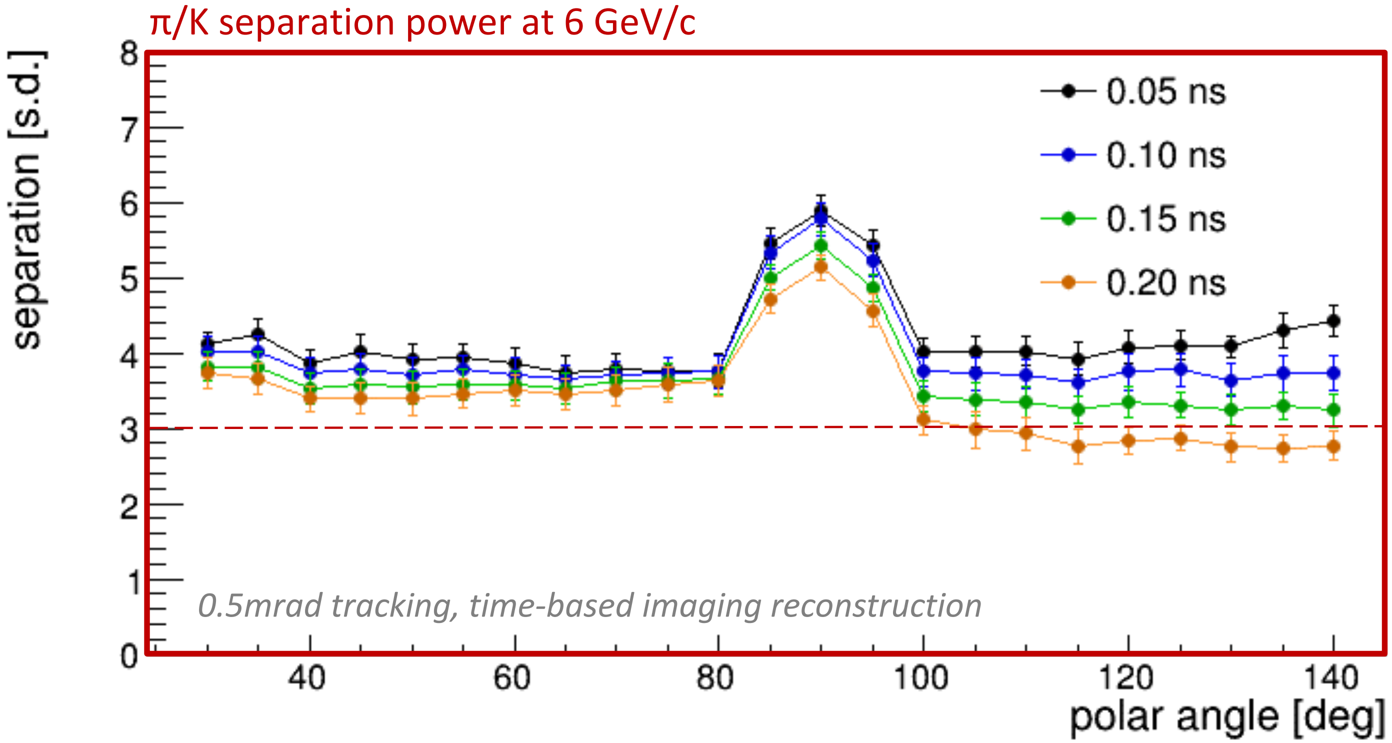


π/K separation power at 6 GeV/c



updated simulation results, summer 2020

HPDIRC PERFORMANCE IN GEANT4



updated simulation results, summer 2020

Radiation Map

Background/radiation

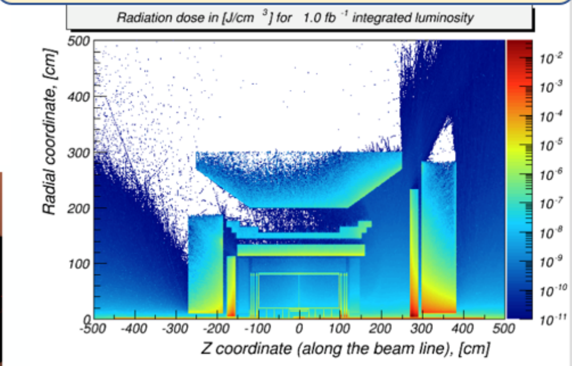
Y. Furletova, EIC@IP6,
IR2@EIC workshop, March 17, 2021

- The HERA and KEK experience show that having backgrounds under control is crucial for the EIC detector performance

- There are several background/radiation sources :
  - primary collisions
  - beam-gas induced
  - synchrotron radiation

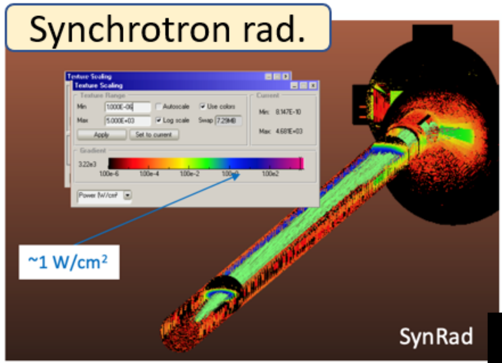
- The design of absorbers and masks must be modeled thoroughly

Primary collisions/ionizing radiation

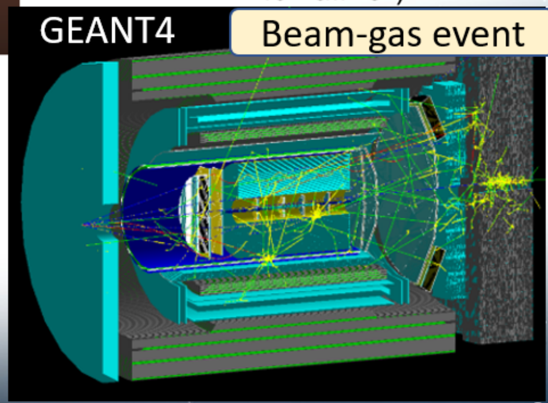


-> backward EmCal: ~250 rad/year (at a "nominal" luminosity ~10^{33} cm^{-2} s^{-1})

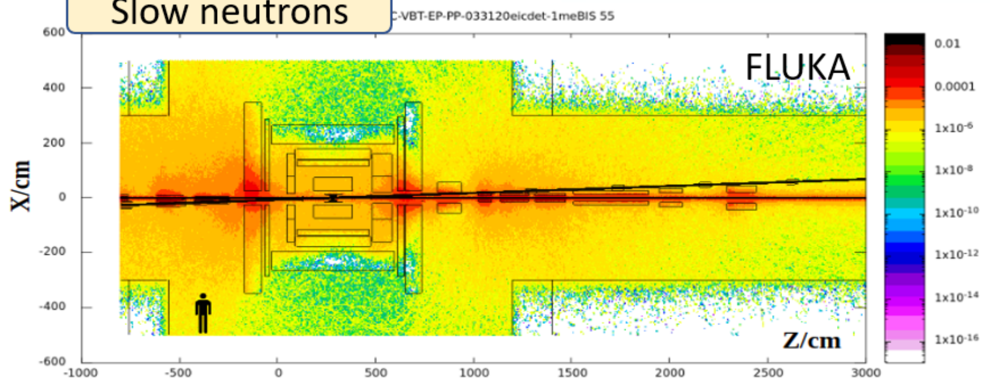
Synchrotron rad.



Beam-gas event

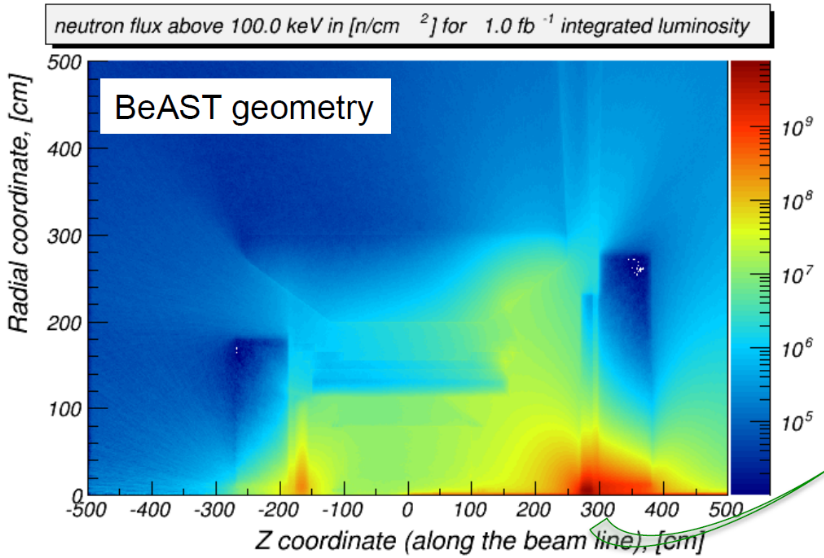


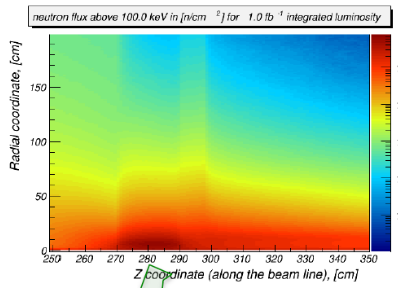
Slow neutrons



Neutron fluence from primary interactions

The quantity: Fluence = "a sum of neutron path lengths"/"cell volume" for N events





-> forward EmCal: up to ~$5 \cdot 10^9$ n/cm^2 per fb^{-1} (*inside the towers*); perhaps ~5 less at the SiPM location;

NB: "standard" EIC run at ~10^{33} cm^{-2}s^{-1} luminosity is 10 fb^{-1}

The numbers look OK, but:

- Beam line elements not incorporated in the simulation
- Thermal neutrons are not accounted
- Close to beam line: ~10^{34} cm^{-2}s^{-1} over ~10 years would exceed ~10^{11} n/cm^2

Simulation for primary interactions

EicRoot Monte Carlo, PYTHIA, BeAST geometry

No beam-gas, no synchrotron radiation,
no thermal neutrons

Fluence from 2D color map to be scaled by factor 100 for 10 year running at high luminosity.

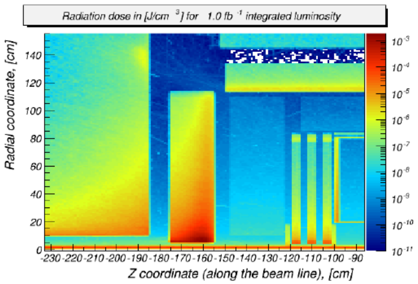
Expect less than 10^9 neutrons cm^{-2} per year at potential DIRC lens locations.

Will use safety factor 100 – 10,000 for neutron irradiation campaign this fall.

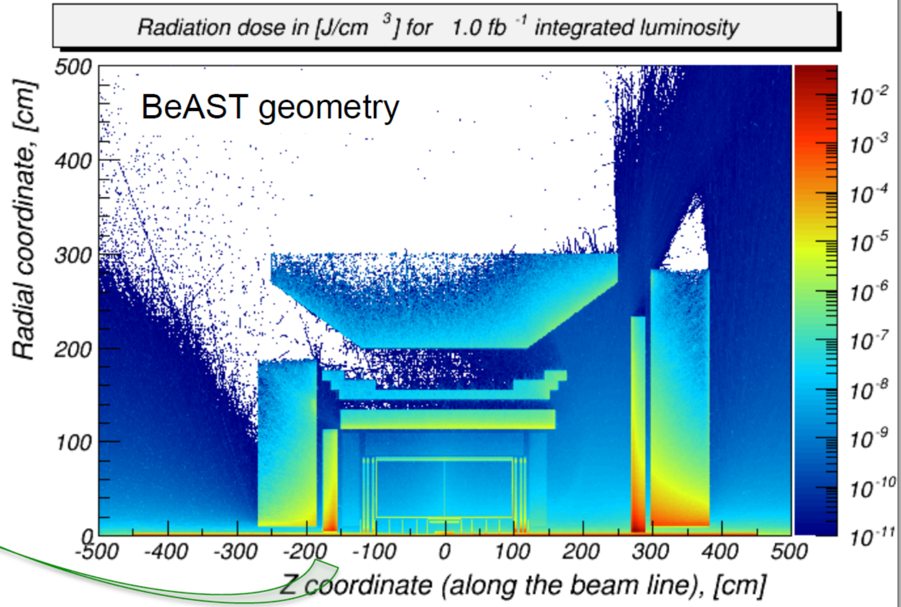
Slide presented by
Yulia Furletova (JLab) and Alexander Kiselev (BNL)
EICUG Yellow Reports Kick-off Meeting, MIT December 2019

Radiation dose from primary interactions

The (primary) quantity: E_{sum} = "a sum of dE/dx"/"cell volume" for N events



-> crystal EmCal: up to ~2*10^{-3} J/cm^3 per fb^{-1} (close to beam line)



1 rad = 0.01 Gy & [Gy] = [J/kg] & PWO density ~8g/cm^3 -> ~250 rad/year

(at "nominal" luminosity ~10^{33} cm^{-2} s^{-1})

-> looks OK?

Simulation for primary interactions

EicRoot Monte Carlo, PYTHIA, BeAST geometry

No beam-gas, no synchrotron radiation

Dose from 2D color map to be scaled by factor 100 for 10 year running at high luminosity

Expect less than 100 rad/year at potential DIRC lens locations.

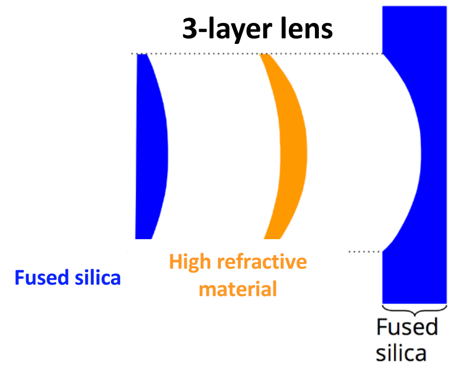
Slide presented by
Yulia Furletova (JLab) and Alexander Kiselev (BNL)
EICUG Yellow Reports Kick-off Meeting, MIT December 2019

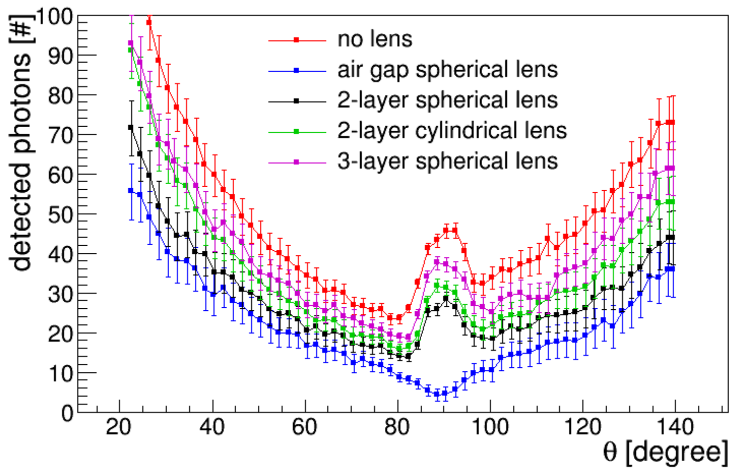
LENS TOPICS

Lens design

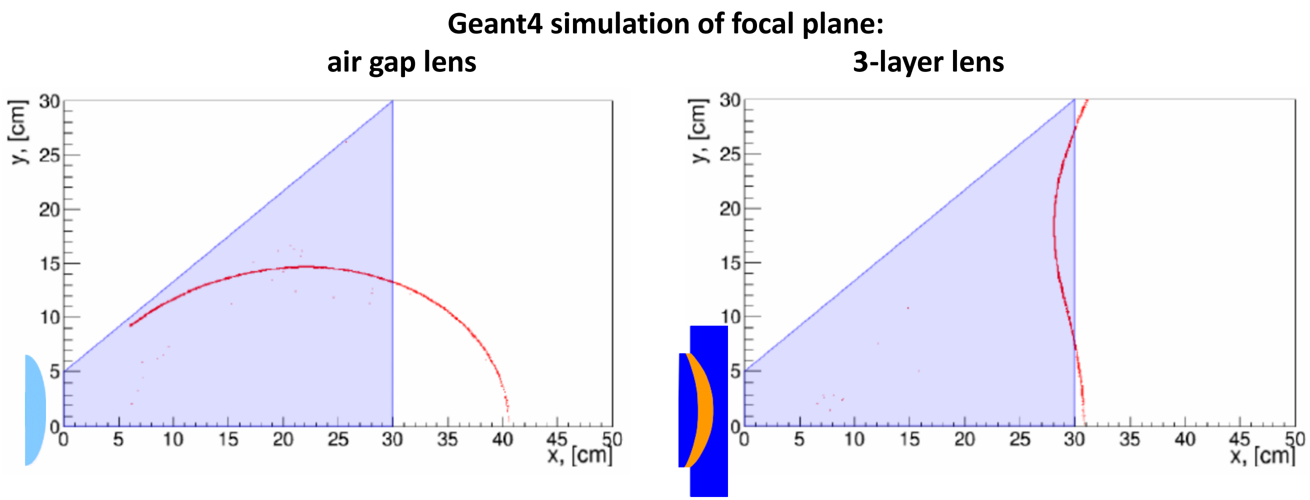
Conventional plano-convex lens with air gap limits DIRC performance

- Significant photon yield loss for particle polar angles around 90°
- Distortion of image plane for photons with steeper propagation angles
- Issues resolved by 3-layer lens with high-refractive index material for middle layer





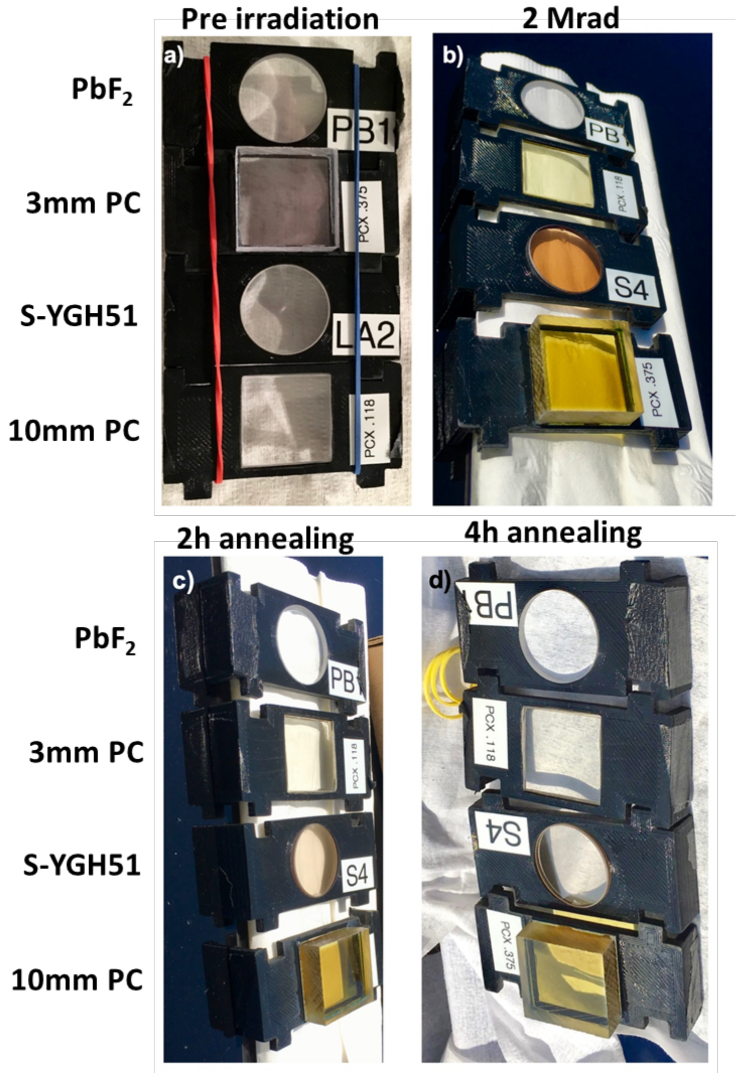
From PANDA Barrel DIRC TDR: simulation



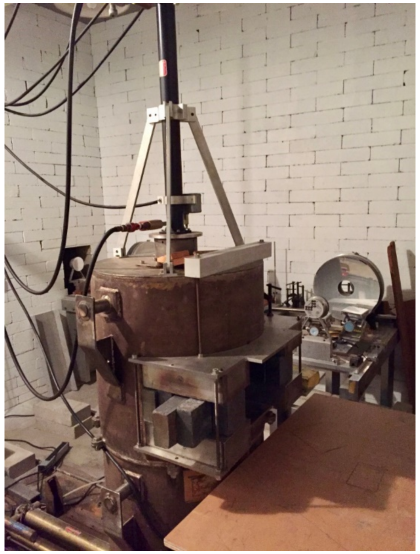
Geant Simulation

hpDIRC Radiation Tests

- Four materials studied up to 2 Mrad:
  - sapphire
  - lead fluoride (PbF_2)
  - lanthanum crown glass (S-YGH51)
  - polycarbonate (PC)
- Sapphire confirmed to be extremely radiation hard. PbF_2 showed very small deterioration.
- Initial photo-annealing and luminescence tests.

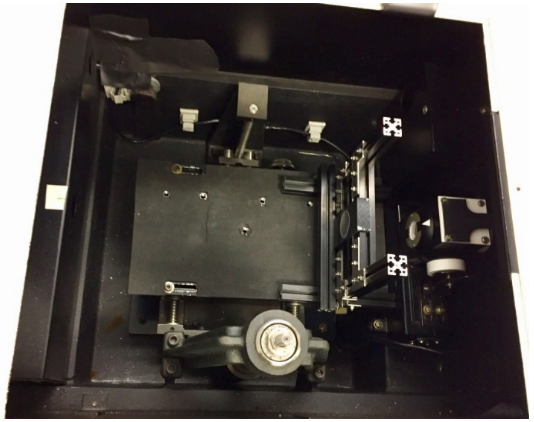


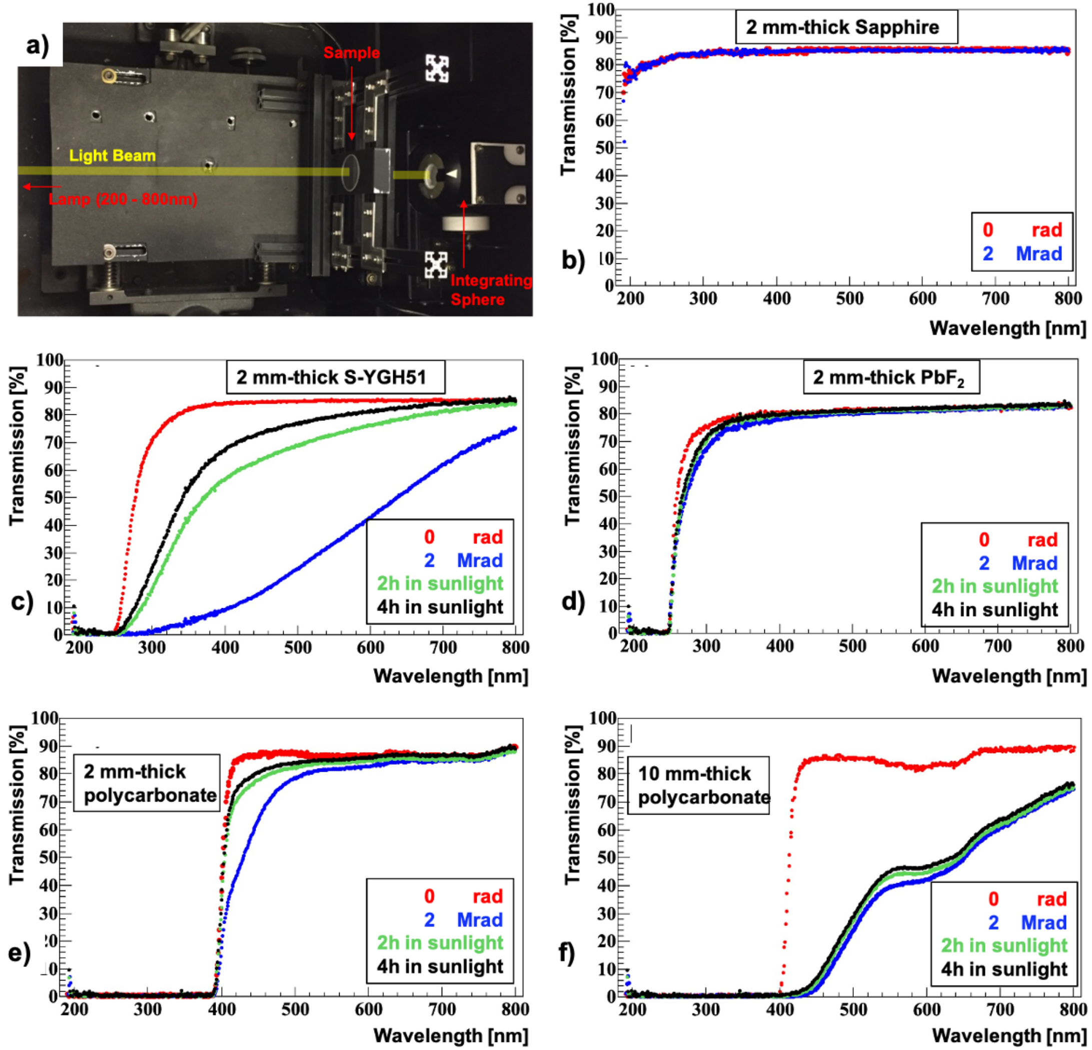
HPDIRC RADIATION TESTS



Co^{60} Chamber

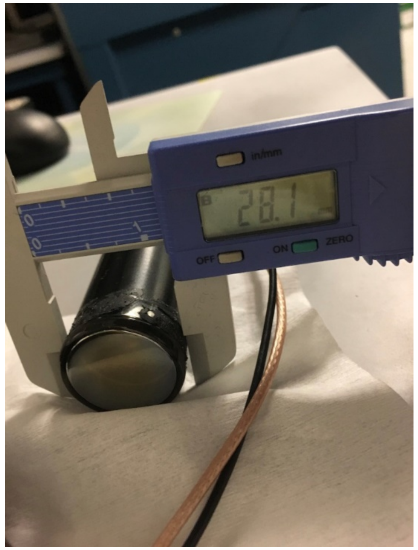
Monochromator

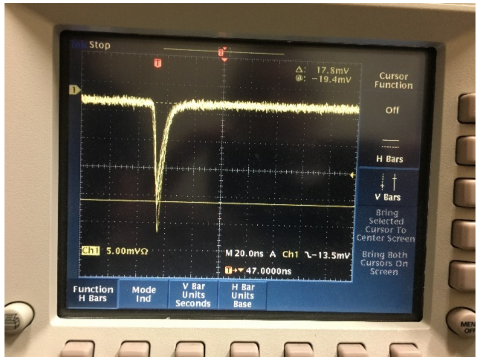




Luminescence Test

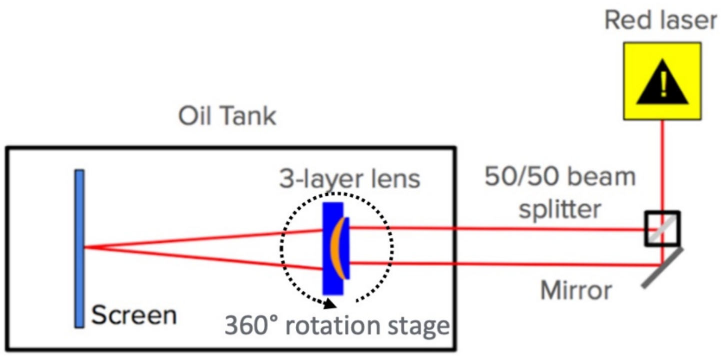
- Samples were pressed against a single photomultiplier tube, wrapped in a light-tight cover.
- The phototube was operated at 1600 V and read out with an oscilloscope.
- The setup was calibrated with a fluoride sample for two tests:
  - luminescence during irradiation with a low dose rate of 2.2 rad/h
  - luminescence a few minutes after irradiation with a high dose rate (17 krad/h)
- No significant observed signal in the PMT after irradiation.
- We did observe a signal during the irradiation for both sapphire and S-YGH51 glass – needs follow-up to quantify.
- No signal was observed for lead fluoride.

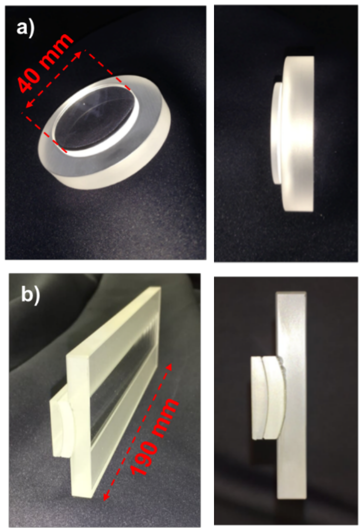


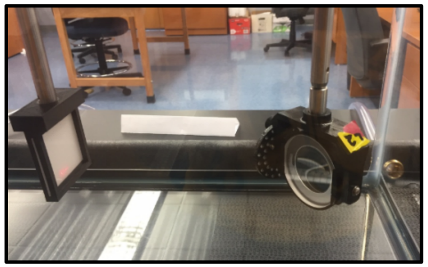


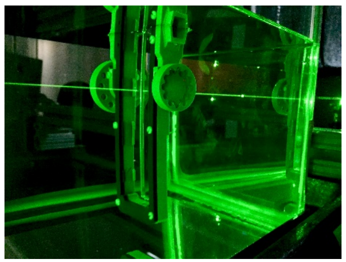
HPDIRC LENS EVALUATION SUMMARY

Laser setup at ODU for mapping the lens focal plane

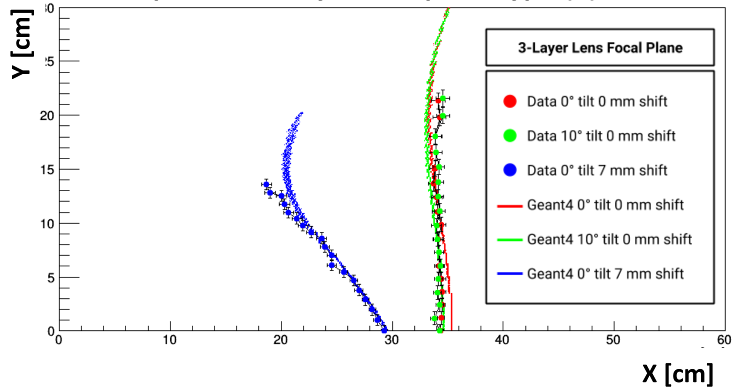




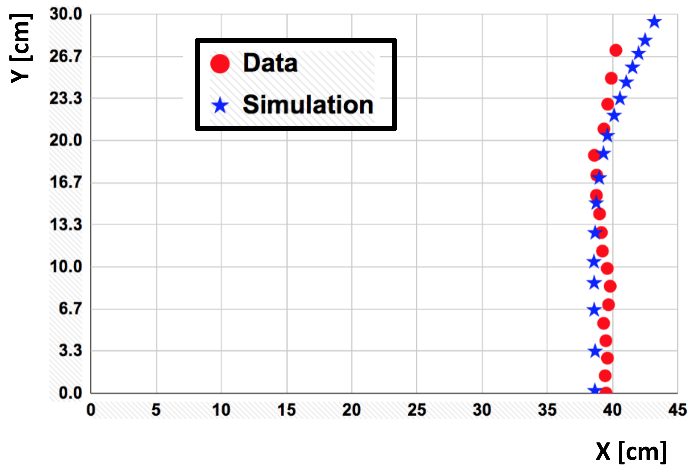




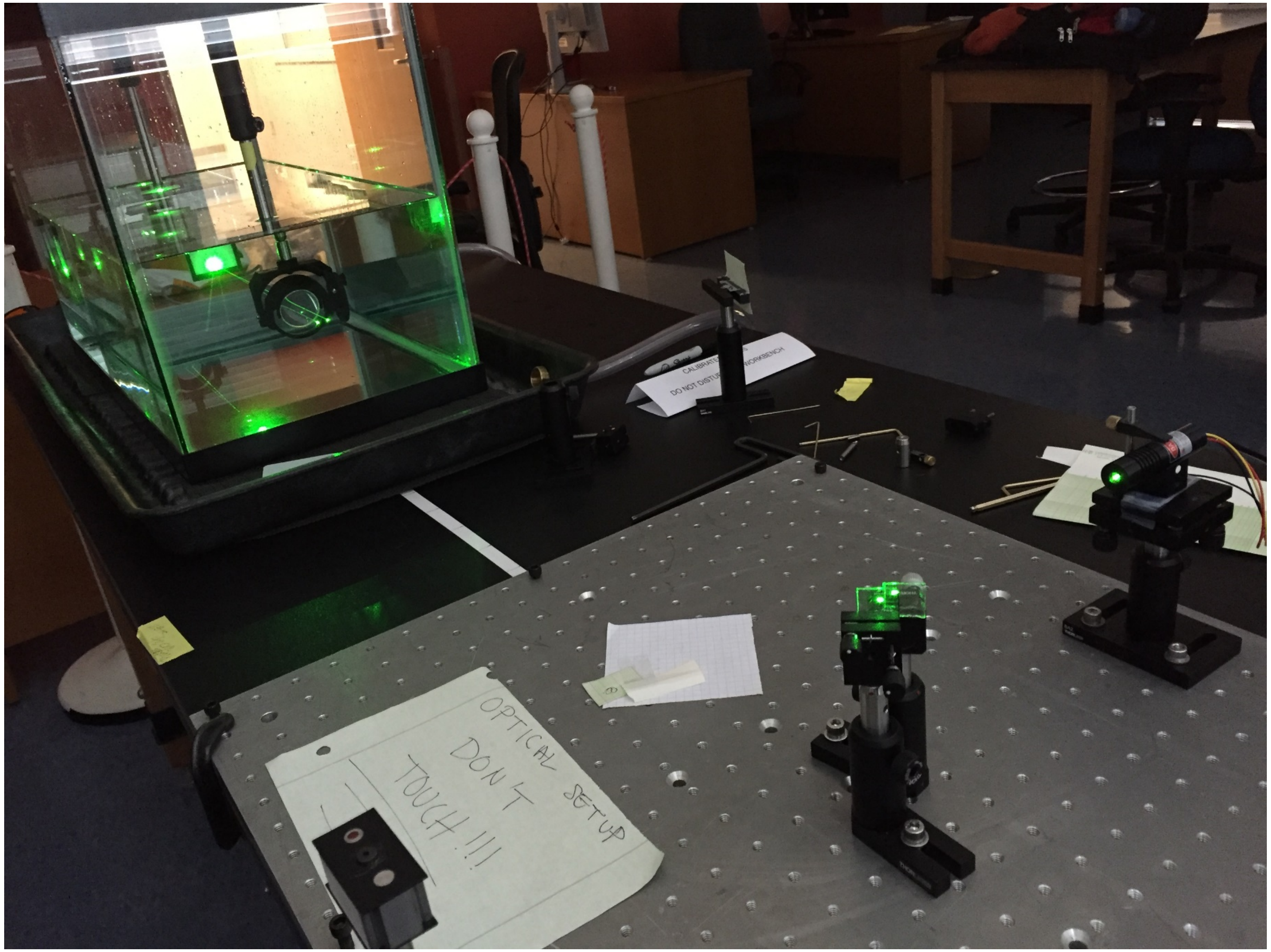
Spherical 3-layer lens prototype (a)



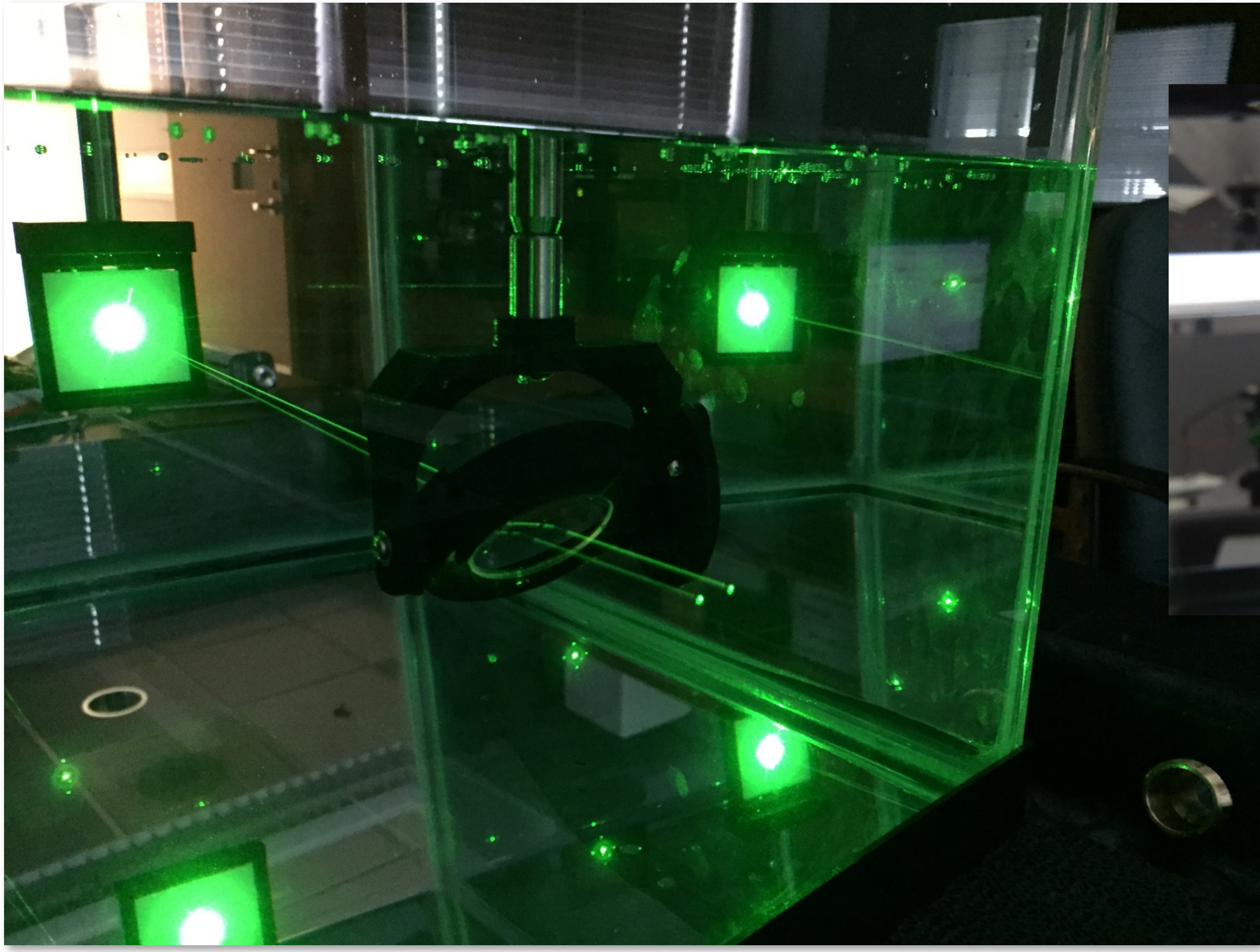
Cylindrical 3-layer prototype (b)

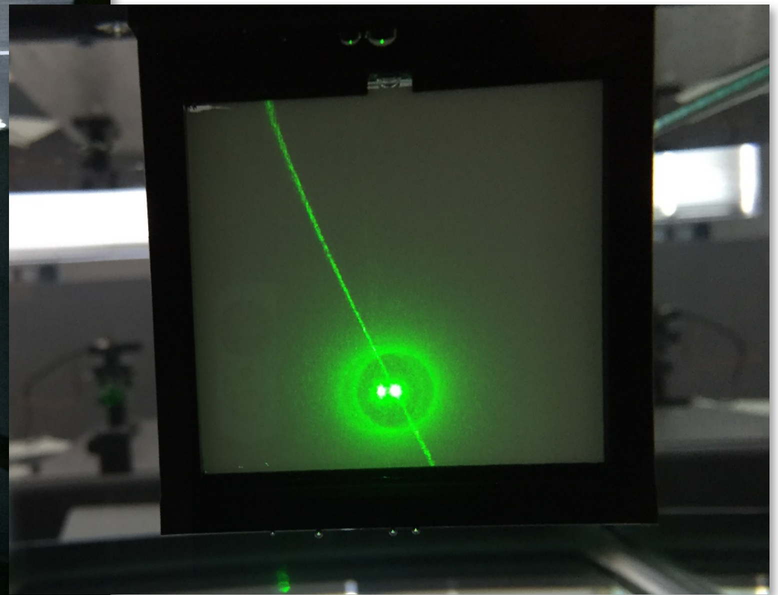


hpDIRC Lens Evaluation Setup



hpDIRC Lens Evaluation Setup





HPDIRC LENS EVALUATION RESULT

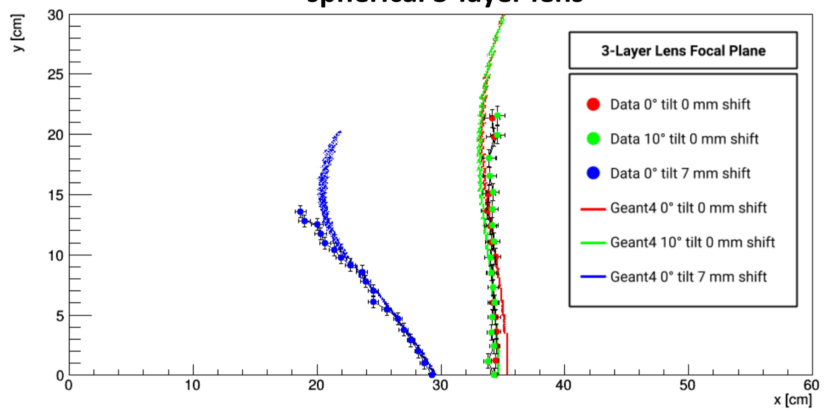
Mapping focal plane of 3-layer lens:

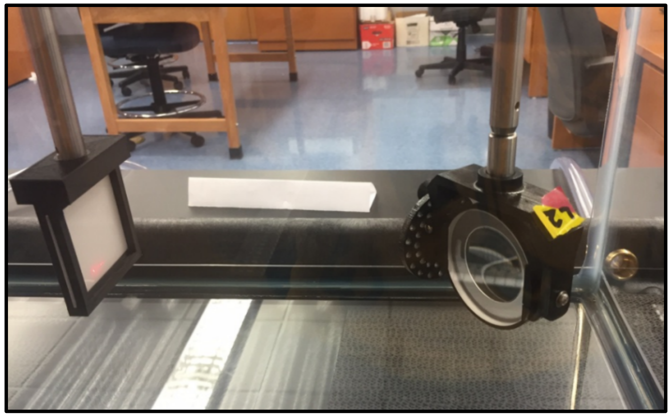
- Lens holder designed to rotate in two planes for the 3D mapping of the focal plane and shifts of lens in horizontal plane.

Spherical 3-layer lens:

- Results of measurements confirm desired flat focal plane for centered laser beams on the lens
- Off-center laser beams in agreement with simulation
- Shape in good agreement but corrections had to be applied to simulation to match absolute value of focal length at zero degrees

Measured and simulated focal plane of spherical 3-layer lens

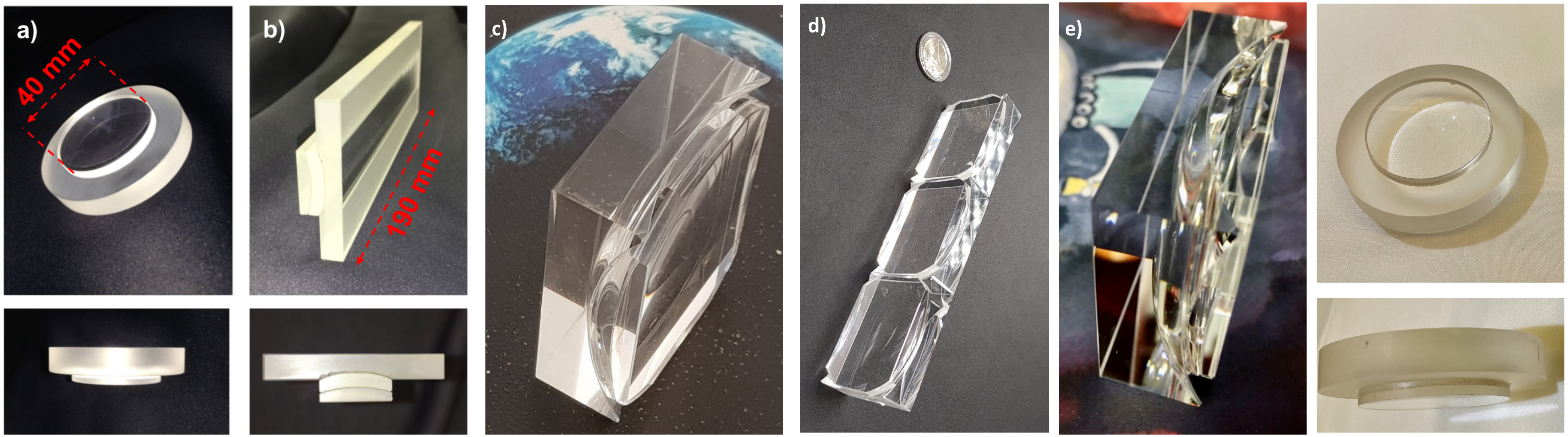




Lens prototypes available for evaluation

- Five 3-layer lenses shown below (some funded by this program, some by PANDA R&D)
- PbF_2 3-layer lens (recently delivered)
- Spherical lens with air gap
- 2-layer spherical lens (PANDA R&D)

Spherical (NLaK33) | **Cylindrical (S-YGH51)** | **Spherical (S-YGH51)** | **Spherical (LaK33)** | **Spherical (Sapphire)** | **Spherical (PbF_2)**



PROTOTYPING

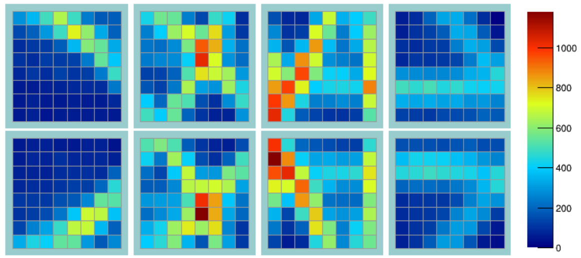
VALIDATION OF HPDIRC SIMULATION

PANDA Barrel DIRC prototype at CERN PS in July/Aug 2018 (reduced number of MCP-PMTs)

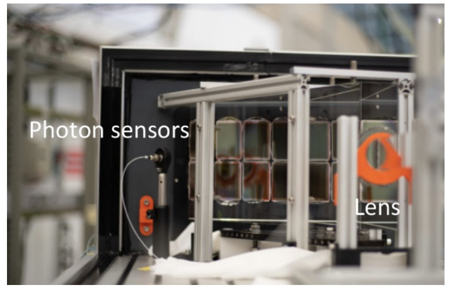
PANDA Cherenkov Group,
Il Nuovo Cimento C 42 02-03
and JINST 15 C03055.

- Caveat: larger sensor pixels, slower electronics than EIC DIRC
  prototype designed for PANDA goal: 3σ π/K separation @ 3.5 GeV/c
- Optics very similar to EIC DIRC design:
  narrow bar, fused silica prism, 3-layer spherical lens
- Measured key quantities: photon yield, Cherenkov angle resolution per photon and per particle, and π/K separation power – all in very good agreement with simulation (same simulation used for EIC DIRC)

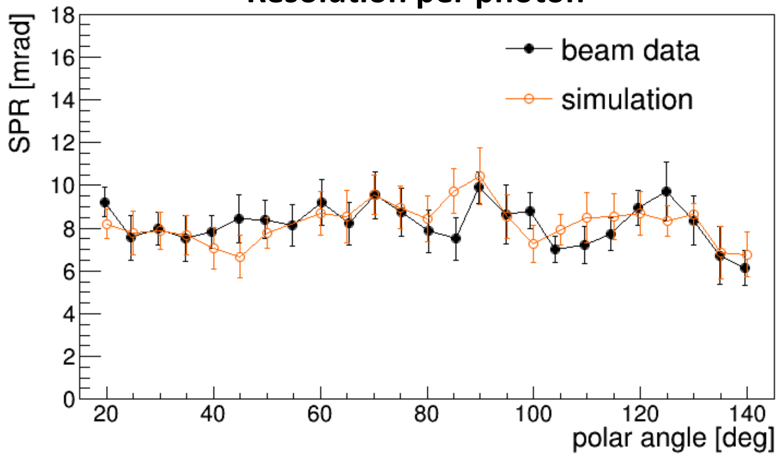
Example of hit pattern



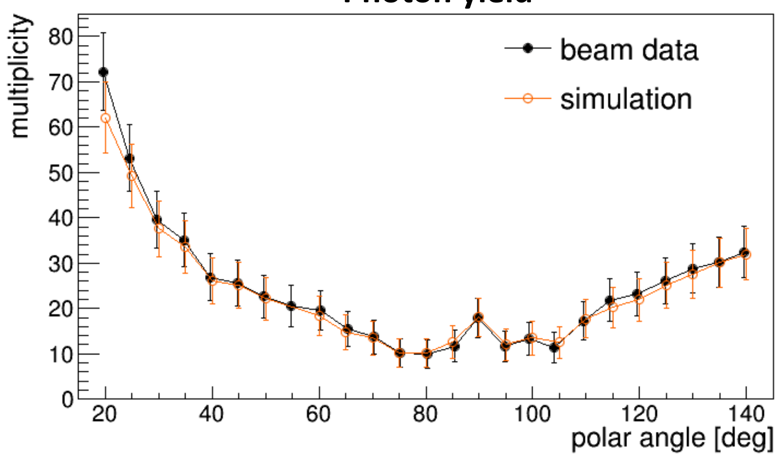
PANDA Barrel DIRC Prototype



Resolution per photon



Photon yield



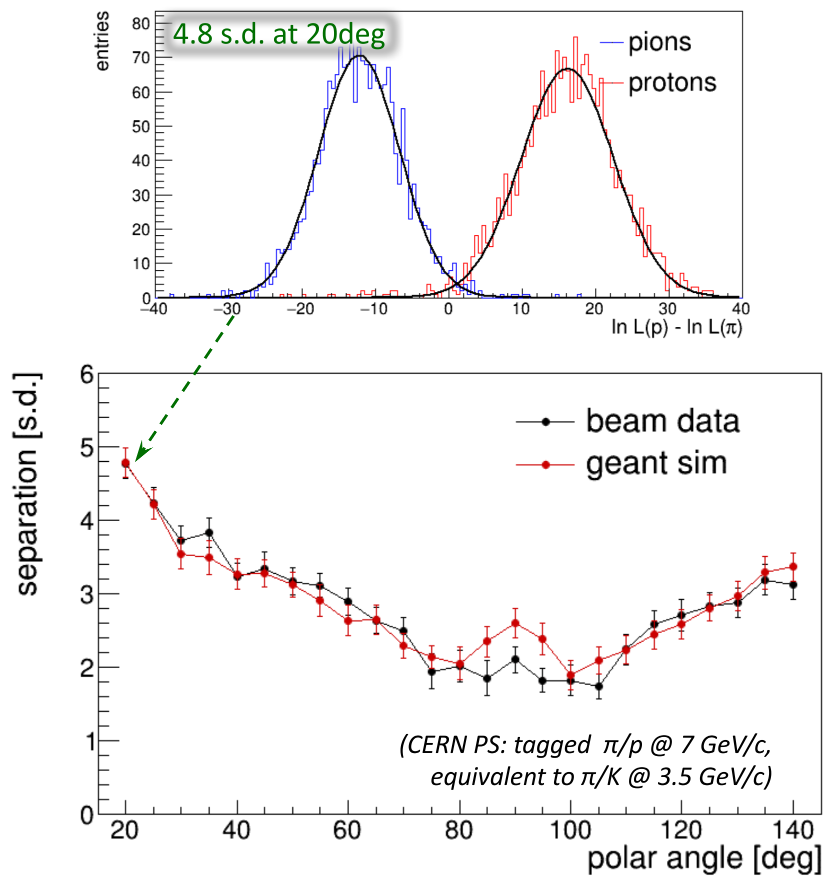
VALIDATION OF HPDIRC SIMULATION

PANDA Barrel DIRC prototype at CERN PS in July/Aug 2018 (reduced number of MCP-PMTs)

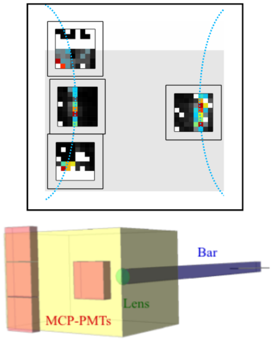
PANDA Cherenkov Group, Il Nuovo Cimento C 42 02-03 and JINST 15 C03055.

- Caveat: larger sensor pixels, slower electronics than EIC DIRC
  prototype designed for PANDA goal: 3σ π/K separation @ 3.5 GeV/c
- Optics similar to EIC DIRC design:
  narrow bar, fused silica prism, 3-layer spherical lens
- Measured key quantities: **photon yield, Cherenkov angle resolution per photon and per particle, and π/K separation power – all in very good agreement with simulation** (same simulation used for EIC DIRC)

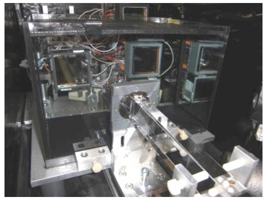
Separation Power

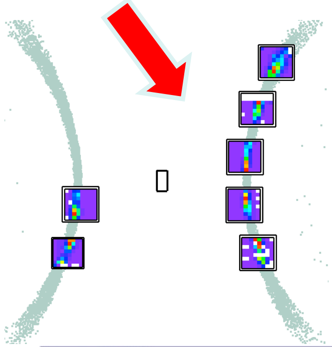


PANDA Barrel DIRC Beam Tests

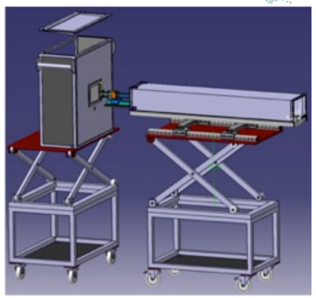


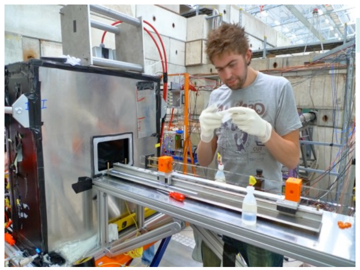
GSI
2008/2009



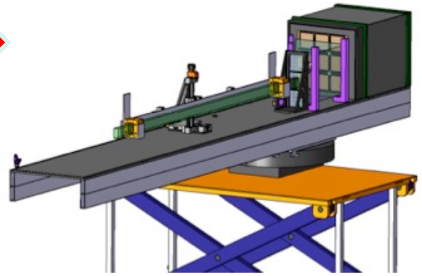


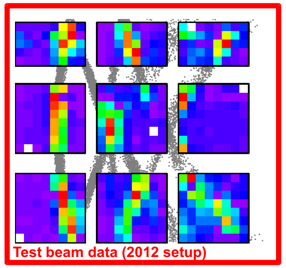
GSI, CERN
2011



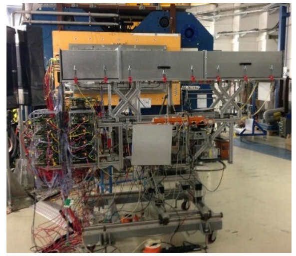


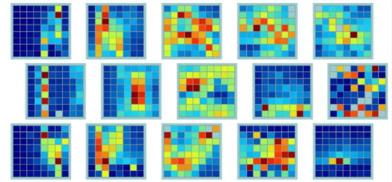
CERN
2012

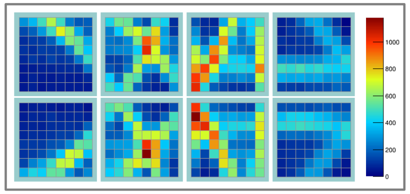




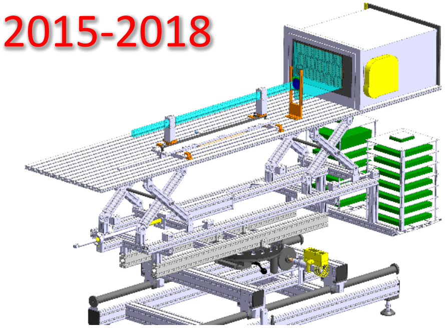
GSI 2014







CERN
2015-2018



Preparation for hpDIRC prototype simulation

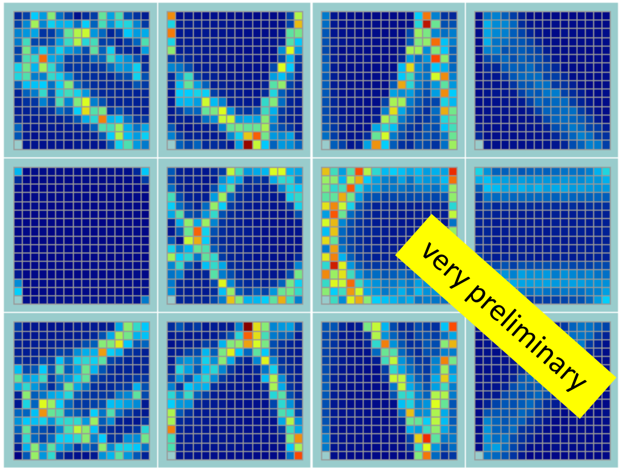
- Start from PANDA Barrel DIRC prototype simulation, assume CERN beam conditions
- Narrow bar, 3-layer spherical lens, fused silica prism (same as PANDA prototype)
- Replace old 8x8 XP85012 Planacons with new 16x16 XP85122 Planacons
- Fully cover focal plane with 12 MCP-PMTs
- Assume 100ps single photon timing precision, time-based imaging reconstruction

- Cleaner hit pattern, better coverage than in PANDA, especially around 90° polar angle

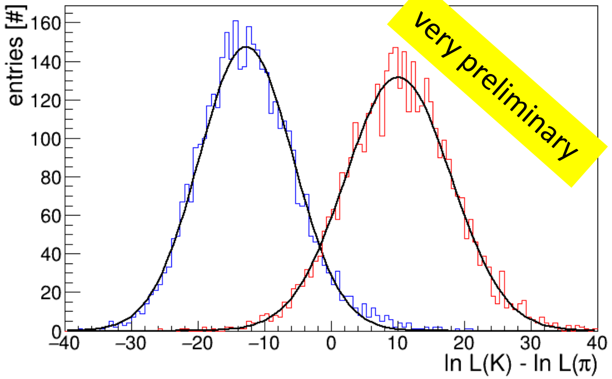
- Very preliminary: 3 s.d. π/K separation at 6 GeV/c feasible with the upgraded prototype

  More information about FTBF beam properties required, needs a lot more work.

Hit pattern for pions, 6 GeV/c, 30°

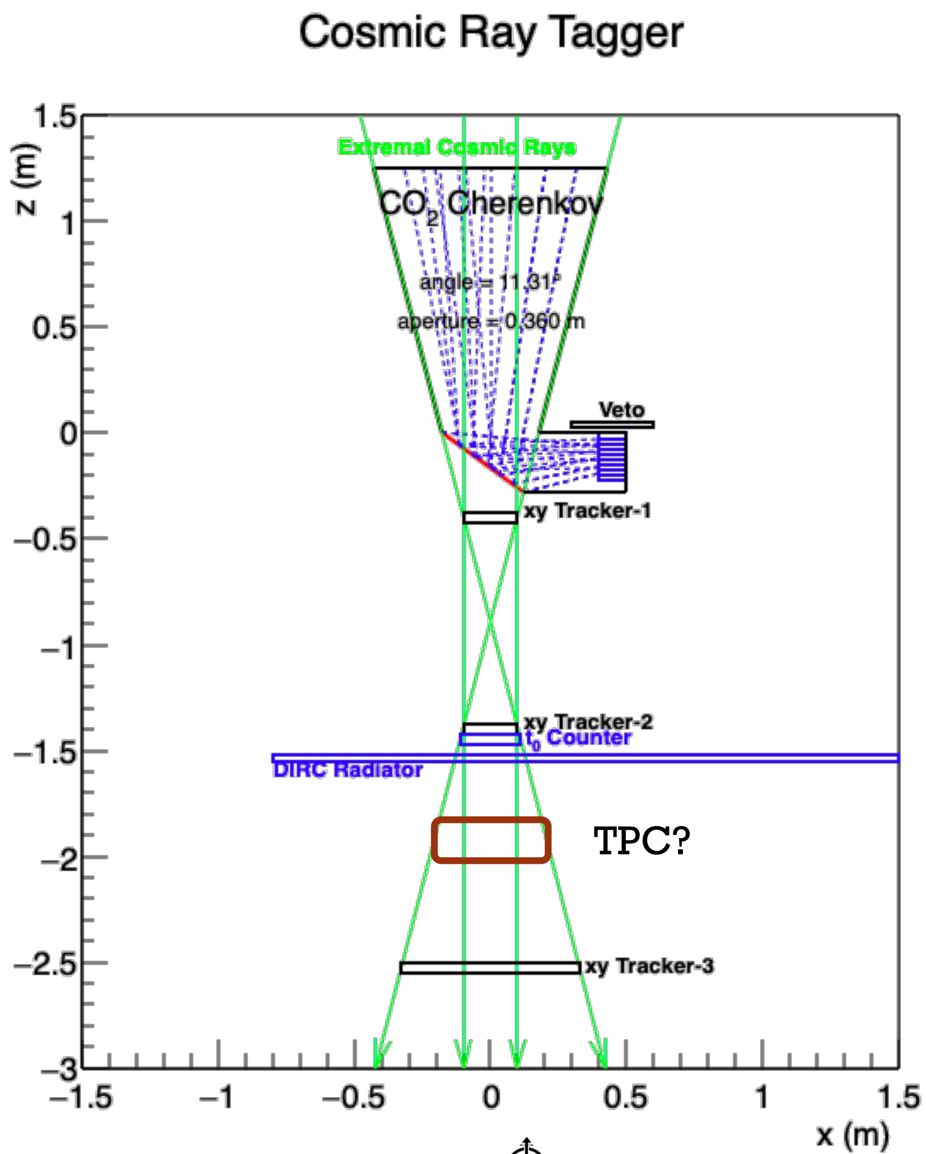


π/K separation, 6 GeV/c, 30°

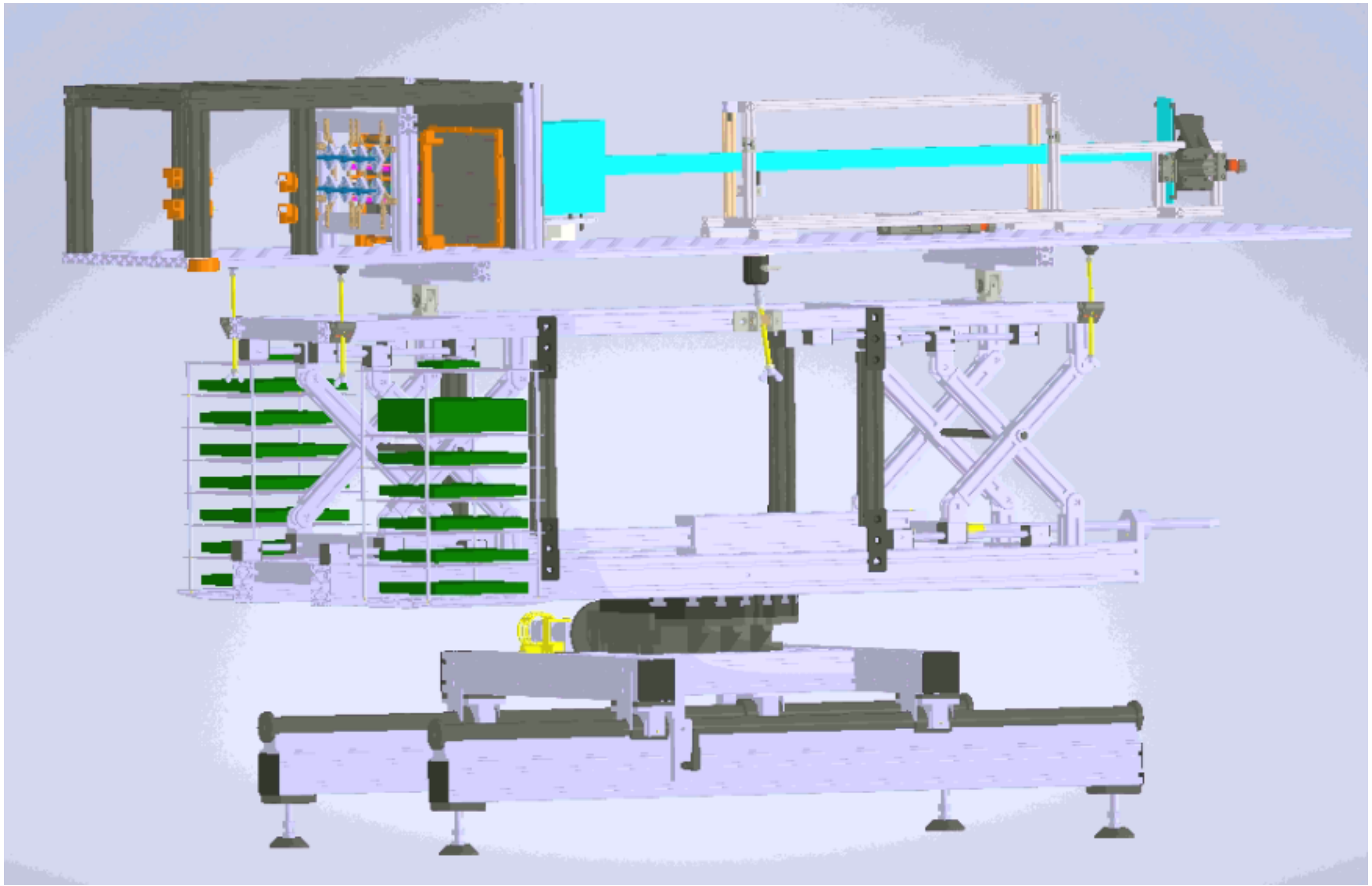


CRT

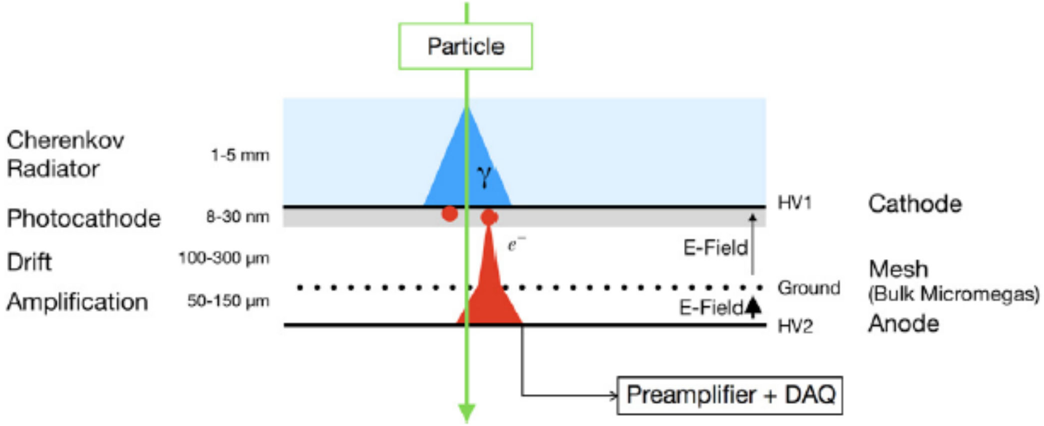
COSMIC RAY TAGGER

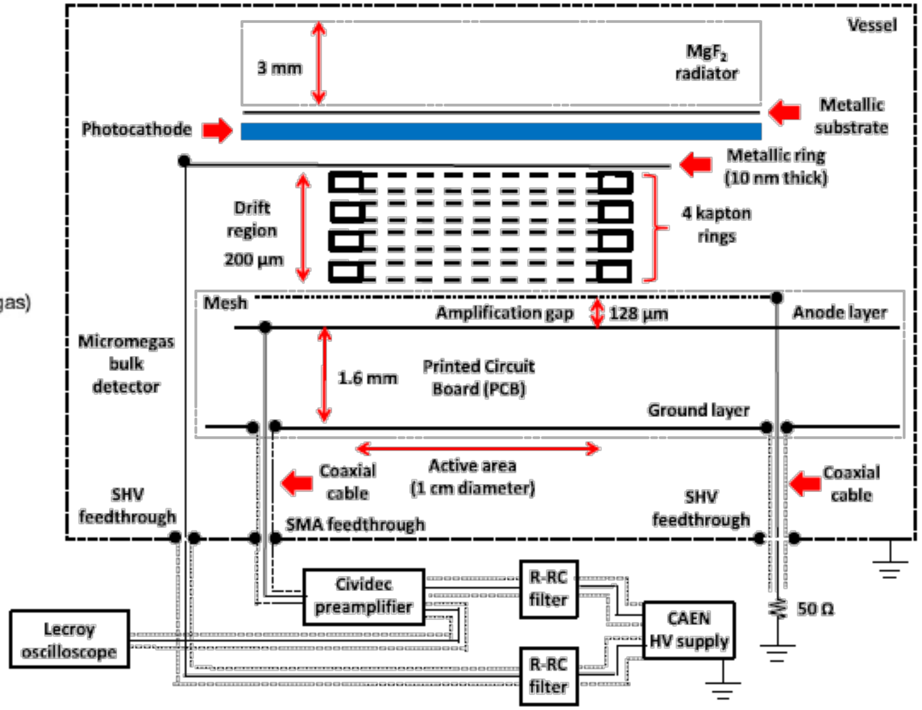


DIRC CAD

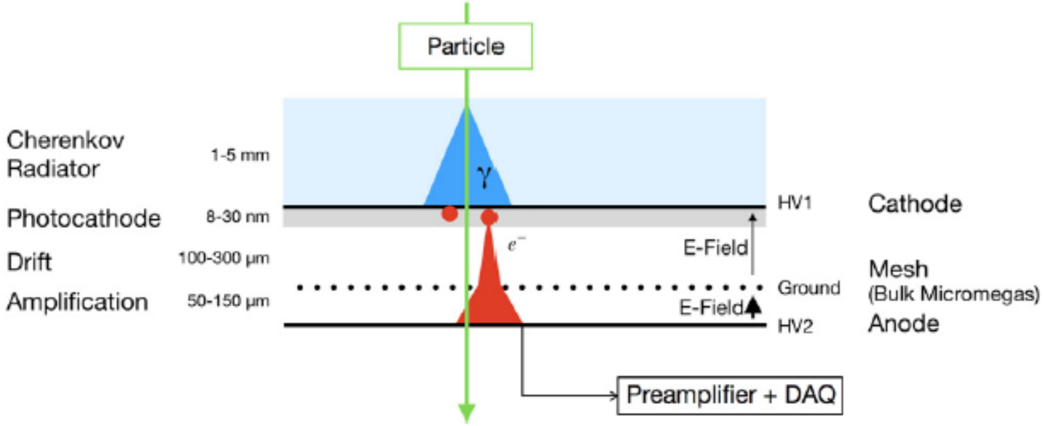


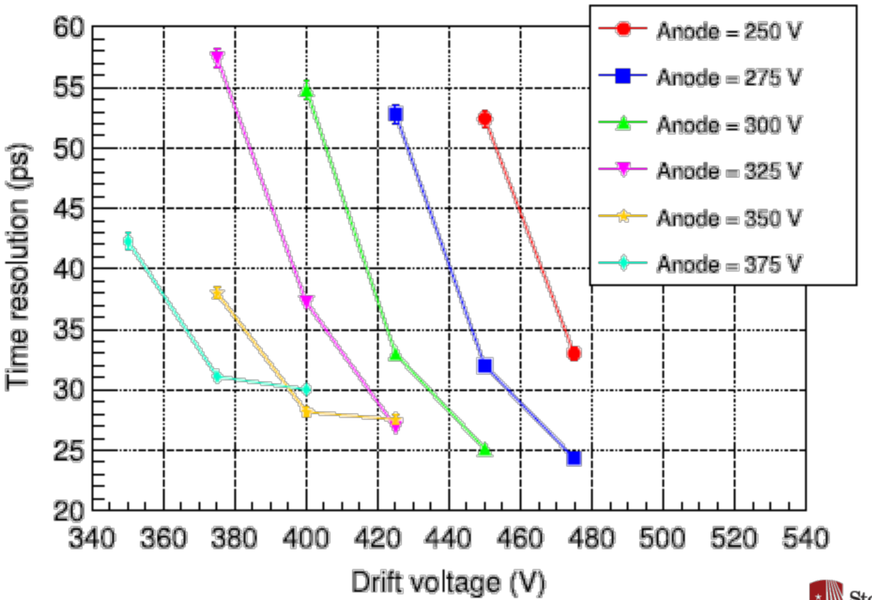
MICROMEGAS PICOSEC-COLLABORATION





MICROMEGAS PICOSEC-COLLABORATION





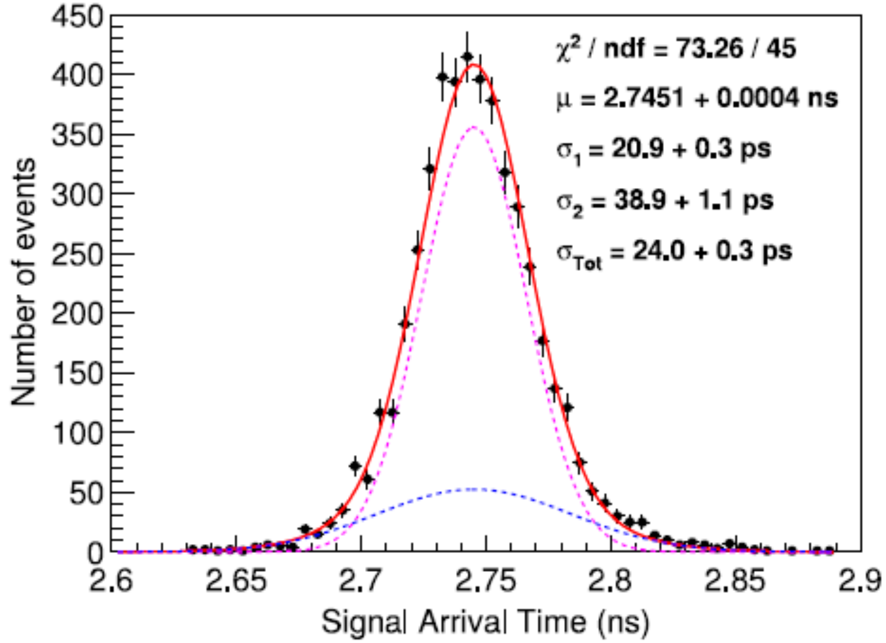


Fig. 13. Beam test: An example of the signal arrival time distribution for 150 GeV muons, and the superimposed fit with a two Gaussian function (red line for the combination and dashed blue and magenta lines for each Gaussian function), for an anode and drift voltage of 275 V and 475 V, respectively. Statistical uncertainties are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)